Vulnerability of critical infrastructure to volcanic hazards

A thesis

submitted in partial fulfilment of the requirements for the degree

of

Doctor of Philosophy in Hazard and Disaster Management

at the

University of Canterbury

by

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UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
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University of Canterbury

2015

Frontispiece

Mt. Ruapehu - April 1945 (photo from my grandmother Marjorie Wilson)

Mt. Ngauruhoe - September 1954 (photo from my grandfather Kenneth Richmond)

Abstract

Volcanic eruptions produce a range of concurrent, sequential and recurrent hazards which can impact society and critical infrastructure. For daily activities, modern societies are reliant on dependable functioning critical infrastructure, such as electrical supply; water supply; wastewater; transportation; communication networks; buildings; air conditioning and ventilation systems; and electronic equipment. In addition, during volcanic eruptions these sectors are vital for effective emergency response and recovery. Despite the importance of critical infrastructure, the systematic quantification of their vulnerability to volcanic hazards, a key aspect of volcanic risk management, has received little research attention. Successful volcanic risk management and disaster risk reduction are cost effective investments in preventing future losses during eruptions and increasing resilience to volcanic hazard impacts. Effective volcanic risk management requires the characterisation of both hazards and vulnerabilities to the same level of detail.

This thesis develops a methodological framework to quantitatively assess the vulnerability of critical infrastructure sectors to volcanic hazard impacts. The focus is on fragility and vulnerability functions which provide quantitative relationships between impact (damage and disruption) and volcanic hazard intensity. The framework details how post-eruption infrastructure impact data, compiled in a newly established infrastructure impacts database, can be classified by hazard and impact intensity to derive vulnerability and fragility functions. Using the vulnerability framework, fragility functions for several critical infrastructure sectors for volcanic tephra fall impacts are derived. These functions are the first attempt to quantify the vulnerability of critical infrastructure sectors using a systematic approach. Using these fragility functions, risk is estimated for the electrical transmission network in the North Island of New Zealand using a newly developed probabilistic tephra fall hazard assessment.

This thesis and framework provide a pathway forward for volcanic risk scientists to advance volcanic vulnerability assessments such that comprehensive and robust quantitative volcanic risk assessments are commonplace in infrastructure management practices. Improved volcanic vulnerability and risk assessments leads to enhanced risk-based decision making, prioritisation of risk reduction investment and overall reduction in volcanic risk.

Acknowledgements

I am extremely grateful to the many people who have offered support, expertise and assistance over the past three years while completing this thesis; it would not have been possible without you.

I must thank my supervisors Dr. Tom Wilson, Dr. Natalia Deligne and Prof. Jim Cole for all your support and encouragement throughout this PhD and prior. I am grateful for the opportunity to work with all of you and I hope it continues in the future. To Tom, thank you for your unwavering support and taking the time to discuss many ideas and thoughts. Your enthusiasm towards my research and natural hazard research in general is much appreciated and a source of inspiration. Thank you also for allowing me to be involved in a number of other research projects. To Natalia, thank you for taking me on as your first PhD student as you began your post-doc at GNS Science and for the excellent chapter reviews to ensure they could be understood by wider audiences. To Jim, thank you for being there to talk things through, quickly review chapters at any time and for being a mentor to me over the past eight years. You have made my time at university more enjoyable.

I would like to thank Prof. Costanza Bonadonna and Sébastien Biass from the University of Geneva who supervised my project for my Specialisation Certificate in Geological and Climate Related Risk (CERG-C). I very much appreciate all the assistance with establishing the project and all the guidance Sébastien provided with computer modelling. Thank you to Corine Frischknecht for organising the CERG-C teaching programme, to all the lecturers for excellent classes and to all the participants of CERG-C 2013 for making the course enjoyable and something to remember.

I acknowledge funding from the following sources, without which this research would not have happened: University of Canterbury Doctoral Scholarship, Determining Volcanic Risk in Auckland (DEVORA), the Ministry of Business, Innovation and

Employment’s Natural Hazard Research Platform, Mason Trust, and the Royal Society of New Zealand Canterbury Branch.

To everyone in our research group, thank you for all the wonderful discussions, fun on research trips and awesome work increasing our understanding of volcanic eruption impacts. Thank you also to Heather Craig for all the discussions, support and the much needed coffee breaks.

Thank you to Mum and Dad for all your assistance and support for the many years I have been at university.

Statement of co-authorship

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Chapter 2 – Volcanic hazard impacts to critical infrastructure: A review.

Published in: Journal of Volcanology and Geothermal Research (Volume 286, pages 148–182).

The published manuscript was compiled and written by Mr. G. Wilson. Dr. Thomas Wilson and Dr. Natalia Deligne contributed significantly to refining and structuring the manuscript. Prof Jim Cole, Dr. Carol Stewart and Dr. Graham Leonard reviewed the manuscript prior to submission.

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Chapter 4 – Framework for volcanic fragility and vulnerability functions

An early version of this chapter was used as a science report prepared for the Volcanic Disaster Preparedness Research Centre (VDPRC), South Korea.

For the business contract between the University of Canterbury and VDPRC Dr. Thomas Wilson was named as the principal investigator. Dr. Wilson proposed the structure of the report and wrote a section (~25%) about agricultural impacts. Mr. G. Wilson wrote the majority (~75%) of this report. Dr. Wilson and Mr. Daniel Blake provided reviews of the report.

For the chapter included here, Mr. G. Wilson changed the content significantly and re-wrote the majority of the material while keeping a similar structure. The agriculture section Dr. Wilson wrote is not included in this chapter and Mr. Blake has not reviewed this chapter. Dr. Wilson and Dr. Natalia Deligne have provided detailed reviews of the chapter and suggestions to its contents. Prof. Jim Cole has reviewed the chapter.

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Chapter 5 – Probabilistic tephra hazard assessment for New Zealand.

Submitted to: New Zealand Journal of Geology and Geophysics.

Submitted: 6 March 2015

An early, and different version of this project was used by Mr. G. Wilson as a report as part of the course requirements for the Specialisation Certificate in Geological and Climate Related Risk (CERG-C) at the University of Geneva, Switzerland (supervised by Prof. Costanza Bonadonna and Mr. Sébastien Biass).

The submitted manuscript was compiled and written by Mr. G. Wilson and substantially changed from the initial CERG-C report (above). Dr. Thomas Wilson, Prof. Bonadonna, Mr. Biass assisted with the scope of the project. Mr. Biass introduced Mr. G. Wilson to the tephra model and assisted with the initial setup of the model. Mr. G. Wilson conducted all subsequent modelling. Dr. Natalia Deligne provided detailed reviews of the manuscript and suggestions to its contents. Dr. Wilson, Prof. Bonadonna, Mr. Biass and Prof. Jim Cole reviewed the manuscript prior to submission.

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Chapter 6 – Volcanic tephra fall risk assessment for New Zealand's electrical transmission network.

Prepared for submission to: Bulletin of Volcanology.

The prepared manuscript was compiled and written by Mr. G. Wilson. Dr. Thomas Wilson contributed significantly to the structure and scope of the manuscript. Dr. Wilson and Dr. Natalia Deligne provided detailed reviews of the manuscript and suggestions to its contents. Prof. Jim Cole reviewed the manuscript.

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Appendix B – Impacts of the 2014 eruption of Kelud volcano, Indonesia, on infrastructure, utilities, agriculture and health

Submitted to: GNS Science as a science report

Mr. G Wilson was second author and contributed to field data collection, writing sections of the report and provided reviews of the report. Mr. Daniel Blake was lead author and wrote the majority of the report and contributed to field data collection. Other co-authors (Dr. C. Stewart, Mrs. H. Craig, Mr. J. Hayes, Dr. S.F. Jenkins, Dr. T.M. Wilson, Dr. C.J. Horwell, Mr. R. Daniswara, Mr. D. Ferdiwijaya, Ms. Supriyati Andreastuti, Dr. G.S. Leonard, Mr. M. Hendrasto, Dr. S. Cronin) contributed to field data collection, writing and reviewing the report.

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Chapter One – Introduction

1.1 Volcanic eruptions

Volcanic eruptions are powerful and uncontrollable natural phenomena. Eruptions produce a range of hazards depending on the style and explosivity, from effusive (passive lava flows) through to explosive activity (Lockwood and Hazlett, 2010). Rapid-onset hazards such as pyroclastic density currents (PDCs), lahars, ballistics and lava flows can be highly dangerous and damaging in proximal locations. Tephra falls and gas emissions are lower-impact hazards but can have effects hundreds of kilometres away from the vent (T.M. Wilson et al., 2012). Volcanic hazards can occur simultaneously or sequentially and over differing spatial and temporal (hours to decades) scales, with any one volcano exhibiting a range of possible hazards. See Table 1.1 for descriptions of common volcanic hazards.

There are an estimated 800 million people worldwide living within 100 km of active or potentially active volcanoes (Brown et al., 2015). These people, and their associated built environment, are exposed to the effects of potential volcanic hazards in the case of an eruption. As global population increases and communities expand into volcanic environments, as a result of development pressures or to take advantage of fertile volcanic soils, exposure and vulnerability to volcanic hazards will increase (Chester et al., 2000). While fatalities and economic losses associated with volcanic eruptions are small compared to earthquakes, floods and droughts, they are still significant. Between 1600–2010 CE, volcanic eruptions have caused approximately 280,000 fatalities, with PDCs responsible for the largest proportion (33%) of these fatalities (Auker et al., 2013). Economic losses are not as easily quantified as fatalities but are considerable (Sparks et al., 2013). This has been illustrated recently during the 2010 eruption of Eyjafjallajökull, Iceland, which forced the closure of European and North Atlantic airspace for six days (Sammonds et al., 2010), resulting in global financial losses of approximately US$5 billion (Ragona et al., 2011).

Table 1.1: Simplified descriptions of composition, occurrence and potential impacts (excluding impacts to people) of common volcanic hazards.

Volcanic hazard	Description
Pyroclastic density currents (PDC)	Mixtures of hot gas and pyroclastic particles which rapidly travel downhill and spread into the surrounding area.[a]
	Cause damage and destruction to the built environment due to high dynamic pressures and temperatures.[b]
	Deposits can bury buildings, infrastructure and land.
Lava flows	Outpourings of molten rock from volcanic vents or fissures which flow downhill at moderate velocities and harden upon cooling.[c]
	Flows bury land and assets in their path and ignite combustible materials.[d]
Lahars	Gravity-driven volcanic mud- or debris-flows comprised of pyroclastic material, rock fragments and water which typically sweep down off volcano slopes.[e]
	Secondary lahars can occur for many years after an eruption.
	Cause damage and destruction to the built environment due to high dynamic pressures and deposits can inundate buildings, infrastructure and large areas of land.[f]
Ballistics	Large particles (>64 mm) ejected at high energy during explosive eruptions which can travel up to 10 km from the vent.[g]
	Cause damage to the built environment and can cause fires.[h]
Tephra fall	Pyroclastic particles (<64 mm; volcanic ash <2 mm) ejected during explosive eruptions and widely dispersed in volcanic plumes for thousands of kilometres.[i, j]
	Particles are coated in a range of soluble salts following interactions with volcanic gases in the plume.[k]
	Thick deposits can cause collapse of buildings from increased static load.[h]
	Abrasion damage occurs on components with moving parts and corrosion can occur on metal surfaces.
	Tephra can cause disruption due to its presence, the need to remove it from components or from electrical short circuits.[l, m]
Gas emissions	Emission and dispersal of different gas species during an explosive eruption or passive degassing at a vent.[n]
	Can cause corrosion of metals.[o, p]

[a] Wilson and Houghton (2000); [b] Baxter et al. (2005); [c] Kilburn (2000); [d] Peterson and Tilling (2000); [e] Parfitt and Wilson (2008); [f] Rodolfo (2000); [g] Steinberg and Lorenz (1983); [h] Blong (1984); [i] Lockwood and Hazlett (2010); [i] Heiken and Wohletz (1985); [k] Witham et al. (2005); [l] Wardman et al. (2012); [m] T.M. Wilson et al. (2012); [n] Delmelle and Stix (2000); [o] Oze et al. (2013); [p] Watanabe et al.(2006).

Volcanic eruptions are difficult to predict (Brown et al., 2014). However, progress has been made in forecasting eruptions, undertaking pre-emptive hazard assessment, conducting volcanic surveillance and implementing crisis management in order to reduce the impact of volcanic eruptions on society (Sparks et al., 2013). One aspect of modern society that is commonly and sometimes severely disrupted and damaged by volcanic hazards is critical infrastructure (Blong, 1984; T.M. Wilson et al., 2012). This thesis addresses and investigates critical infrastructure vulnerability to volcanic hazards, an area which has received less research attention in the past as researchers have focused on loss of life aspects.

1.2 Critical infrastructure and volcanic hazards

Critical infrastructure are networks of man-made systems and processes that function collaboratively to produce and distribute essential goods and services for society (Rinaldi et al., 2001; Dunn et al., 2013). Reliable and resilient infrastructure are critical for sustainable development, business competitiveness and reputation (UNISDR, 2013). Critical infrastructure includes: electrical supply; water supply; wastewater; transportation; communication networks; buildings; heating, ventilation and air conditioning (HVAC) systems; and electronic equipment.

Critical infrastructure is commonly and sometimes severely impacted by all volcanic hazards (Chapter 2; Blong, 1984; T.M. Wilson et al., 2012). The occurrence and intensity of infrastructure impacts is dependent on hazard characteristics and intrinsic infrastructure properties. Impacts range from service disruption through to complete destruction. Disruption typically occurs as a result of tephra fall or from low intensity volcanic flows. Destruction occurs in proximal areas as a result of high intensity volcanic flow and ballistic impacts. Infrastructure has also been observed to tolerate volcanic hazards and continue operating uninterrupted during eruptions (Chapter 2). Figure 1.1 previews volcanic hazard impacts to critical infrastructure sectors from research conducted in Chapter 2.

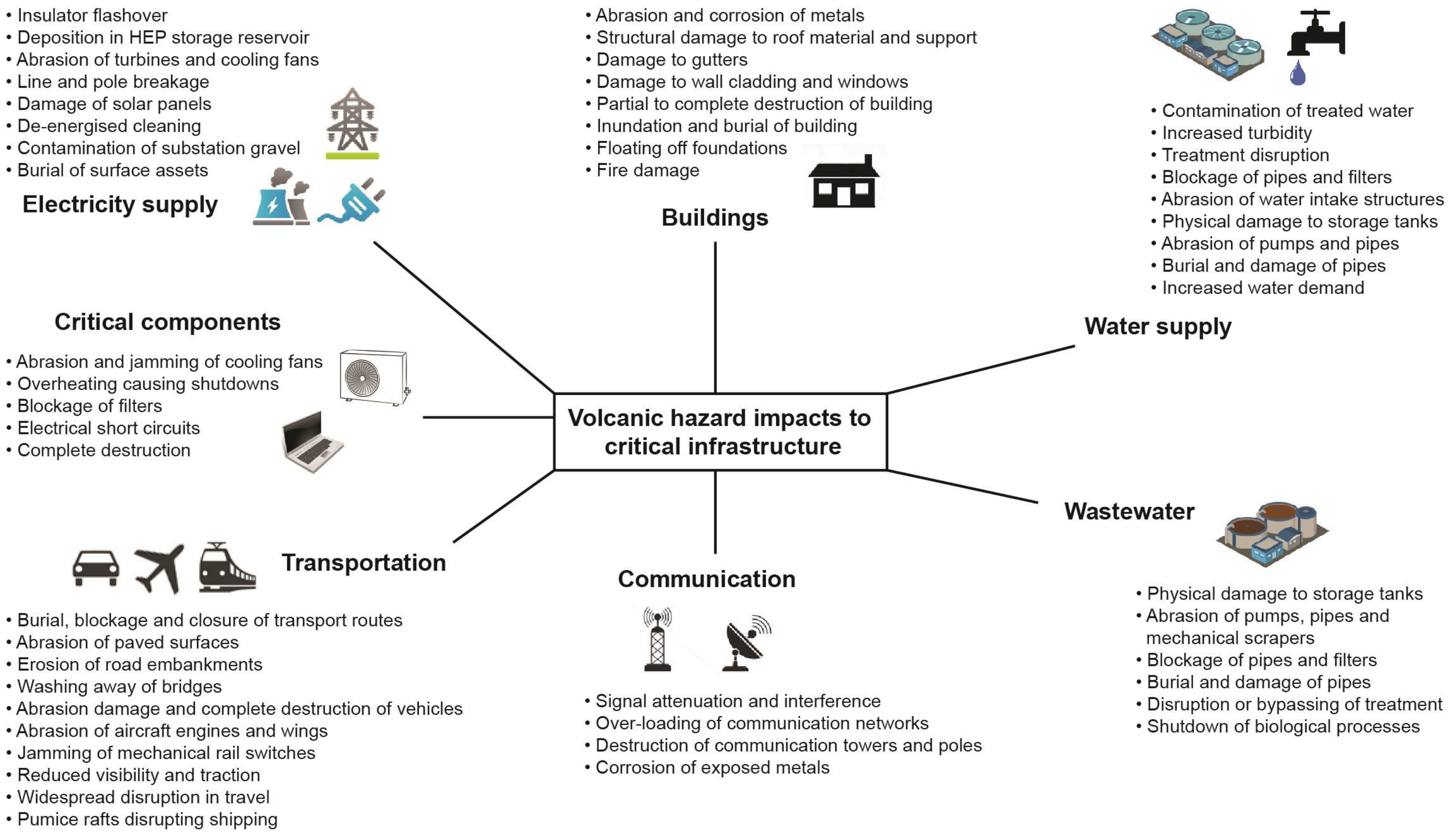

Figure 1.1: Preview of volcanic hazard impacts to different critical infrastructure sectors (see Chapter 2 for further discussion).

There is increasing global awareness of the need for societies to be resilient to natural hazard impacts (UNISDR 2015a). Critical infrastructure must also be resilient to hazards (NIU, 2011, 2014), including volcanic eruptions, as infrastructure is vital for disaster response and recovery and the overall resilience of society. The current approaches for increasing infrastructure resilience are related to land-use planning (Burby, 1998; Brody et al., 2007; Glavovic et al., 2010), hazard mitigation (Chang et al., 2014) and planning for post-disaster reconstruction and recovery (Berke and Campanella, 2006; Olshansky, 2006; CERA, 2012). To facilitate these approaches, some governments have established research programmes to assess infrastructure resilience. For example, the National Infrastructure Unit (NIU), a unit of the New Zealand Government, has identified increasing critical infrastructure resilience as one of six guiding principles which will contribute to increasing economic development and quality of life by 2030 (NIU, 2014). Infrastructure resilience is also being addressed as one of the challenges as part of the New Zealand Government's National Science Challenges research programme (MSI, 2014). In addition to these research programmes, critical infrastructure operators are mandated by the New Zealand Civil Defence Emergency Management Act 2002 to operate to their fullest possible extent during and after a disaster (MCDEM, 2002).

While these plans, research programmes and policies dictate what infrastructure operators should achieve with regards to infrastructure resilience, operators still face a complex task of characterising infrastructure vulnerabilities to natural hazards and setting priorities for mitigation strategies (Chang et al., 2014). This can be particularly challenging when considering volcanic hazards, as eruptions are infrequent events and there are limited vulnerability data available for robust quantitative volcanic vulnerability assessment of critical infrastructure. However, continued research, such as this thesis, of infrastructure vulnerability through volcanic risk assessment will lead to improvements in infrastructure resilience to volcanic hazards.

1.3 Volcanic risk assessment and management

Volcanic risk assessment and management fits into the wider disaster risk reduction (DRR) framework promoted by the Hyogo Framework for Action 2005–2015 (UNISDR, 2007) and now by the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015b). Disaster risk reduction aims to: (1) identify the occurrence of a future disaster; (2) determine what the consequences will be and whether they are societally acceptable or not; and (3) implement proactive planning to mitigate likely impacts in a cost-effective manner. This thesis addresses aspects of aims 1 and 2 by developing a tephra fall hazard assessment for the North Island of New Zealand (Chapter 5) and assessing the consequences of volcanic eruptions on critical infrastructure (Chapters 2–4 and 6). These aspects are addressed in the context of volcanic risk assessment which comprises hazard, exposure, vulnerability and capacity assessments.

Volcanic risk assessments determine risk posed to an area and provide information on risk reduction treatments to lower risk and increase resilience (Papathoma-Köhle et al., 2011). Early volcanic risk and impact assessments in New Zealand (e.g., Patterson, 1987; Johnston and Nairn, 1993; Daly and Wilkie, 1999) focused on using deterministic hazard scenarios to estimate impacts to critical infrastructure, buildings and agriculture. Based on the fixed hazard scenarios, impact to different infrastructure sectors was estimated based on qualitative estimates of impact type and likelihood. While these studies provide advancement in moving from hazard to impact (Daly and Johnston, 2015), the resulting risk assessments are qualitative in nature. However, these studies provide a valuable basis for improved risk assessment in subsequent work (e.g., www.devora.org.nz; DEVORA, 2015) and this thesis. Presently there is an increasing desire for quantitative probabilistic risk assessments for volcanic risk management to overcome the limitations of deterministic approaches (e.g., Marzocchi et al., 2004; Neri et al., 2008; Schmidt et al., 2011; Jenkins et al., 2012a, b). Compared to qualitative approaches, quantitative approaches facilitate consistent and comparable assessments and allow risk reduction treatments to be prioritised. Quantitative risk assessments also feed into, and are critical for, assessing the costs and benefits of public and private investments in risk mitigation and development (UNISDR, 2015a). Results of these assessments can be presented using qualitative descriptions to facilitate effective communication between various stakeholders (Uzielli et al., 2008; Jelínek et al., 2012). Comprehensive and appropriate volcanic risk assessments require that hazard, exposure, vulnerability and capacity aspects all be assessed to the same level of detail.

A large focus of volcanology research has been on characterising the occurrence and dynamics of different volcanic hazards. Without a sound knowledge of volcanic hazards there is little point in planning and implementing risk reduction treatments (Brown et al., 2015). Hazard maps, which show hazard footprints based on geological or modelling evidence, are a common hazard assessment approach for many volcanoes (e.g., Parra and Cepeda, 1990; Artunduaga and Jiménez, 1997; Haynes et al., 2007; Alatorre-Ibargüengoitia et al., 2012; Leonard et al., 2014). Deterministic hazard scenarios, typically based on previous or analogous eruptions, are also commonly used for hazard assessments (e.g., Johnston and Nairn, 1993; Johnston et al., 1997; Schmidt et al., 2011). However, geological and deterministic approaches may not account for all possible future events, as not all events will be recorded in the geological record (Bonadonna, 2006; IAEA, 2013; Brown et al., 2015) or have occurred yet. Probabilistic hazard assessments (e.g., Chapter 5; Dalziell, 1998; Magill et al., 2006; Hurst and Smith, 2010; Jenkins et al., 2012a), which utilise sophisticated hazard models to output hazard extent and intensity, are increasingly used to overcome this limitation. Quantitative probabilistic hazard assessments reduce both aleatoric (intrinsic in the hazard) and epistemic (linked to scientific knowledge gaps) uncertainty by repeatedly modelling hazard outcomes with a large number of random model input variables. These assessments are still limited by the accuracy and relevance of the input data (Jenkins et al., 2012a). Probabilistic hazard assessments provide the probability that a site will experience a hazard of a particular intensity over a certain timeframe (e.g., tephra thickness of 1 mm at site x has a probability of 0.5 over 100 years).

Elements (e.g., people, agriculture, infrastructure and land) which are exposed to volcanic hazards need to be catalogued to estimate volcanic risk. To obtain the best possible risk and impact assessment, high quality and accurate exposure data are required. Data are typically obtained from existing asset inventories or population distributions held by authorities and infrastructure operators (Schmidt et al., 2011) or global datasets (e.g., OpenStreetMap). Specific data for new research projects are often obtained using standardised field survey methodologies (e.g., Jenkins et al., 2014a). Continued improvement in the systematic collection of exposure data should lead to improvements in volcanic risk estimation.

Vulnerability assessments focus on the susceptibility of exposed elements to the consequences (impacts) of volcanic hazards and are the basis to move from volcanic hazard to risk. Vulnerability is an intrinsic property of exposed elements and can vary significantly in space and time (UNISDR, 2009). The vulnerability of exposed elements, in particular critical infrastructure, is based on data from post-eruption observations, laboratory experiments and expert interpretation of these data (Rossetto and Elnashai, 2003). Simplistic vulnerability assessments provide a qualitative assessment of the type (e.g., Chapter 2; Johnston and Nairn, 1993; T.M. Wilson et al., 2012; Jenkins et al., 2014b) and likelihood (e.g., Daly and Wilkie, 1999) of impacts to infrastructure. These assessments provide descriptions of infrastructure vulnerability based on volcanic hazard intensity thresholds (e.g., tephra will cover road markings with thicknesses between 2–50 mm) or the presence of a hazard (e.g., if lava is present it will completely destroy a road). More complex vulnerability assessments utilise fragility and vulnerability functions (e.g., Paton et al., 1999; Spence et al., 2005; Wardman et al., 2012; G. Wilson et al., 2012) which define quantitative relationships between impact level and volcanic hazard intensity. For example, at a given volcanic hazard intensity, a fragility function can provide the probability an asset will sustain different impact intensities.

Vulnerability assessments are the least developed aspect of volcanic risk assessment, especially for critical infrastructure, where few quantitative studies are available (e.g., Kaye, 2007; Wardman et al., 2012; G. Wilson et al., 2012). There are a number of reasons for this: (1) volcanic hazards are not often considered in infrastructure hazard assessments; (2) volcanic hazards are rarely considered in catastrophe modelling; (3) there are no building or infrastructure design codes for volcanic impacts which would prompt the derivation of functions; and (4) volcanic eruptions are infrequent events (Chapter 2). There are however, a number of studies which have documented impacts and vulnerabilities of critical infrastructure from field observations following eruptions from Mt. Pinatubo in 1991 (e.g., tephra-induced building damage; Spence et al., 1996), Rabaul in 1994 (e.g., tephra-induced building damage; Blong, 2003), Montserrat in 1997 (e.g., PDC-induced building damage; Baxter et al., 2005), Merapi in 2010 (e.g., PDC-induced building and infrastructure damage; Jenkins et al., 2013) and other case studies (e.g., T.M. Wilson et al., 2012; Jenkins et al., 2014a), increasing the research community's knowledge. This thesis builds on early vulnerability research (e.g., Johnston and Nairn, 1993; Daly and Wilkie, 1999) and previous fragility studies to address the current research knowledge gap by developing a methodological framework to derive fragility and vulnerability functions for critical infrastructure impacted by volcanic hazards (Chapter 4). Quantification of vulnerability will lead to improved volcanic risk assessments which can inform risk reduction practices.

Capacity is the combination of all the strengths, attributes and resources available within an organisation or community to achieve agreed goals (UNISDR, 2009). In the DRR space, the goal is typically a reduction in natural hazard risk. Little can be done to control volcanic hazards (Lockwood and Hazlett, 2010) and therefore volcanic risk reduction is focused towards reducing exposure and vulnerability. Volcanic risk can be reduced through mitigation actions such as volcano monitoring, engineering techniques, hazard-resistant construction, land-use planning, government policies and education (UNISDR, 2009). Evacuations have been successfully carried out before and during a number of eruptions (Blong, 1984; Woo, 2008; Sparks et al., 2013; Sword-Daniels,

2014) to remove people from hazardous zones, reducing casualties. Land-use planning, which prevents or limits construction in areas of high volcanic risk, has been used to reduce volcanic risk to people and critical infrastructure, primarily though the establishment of parks around volcanoes (Becker et al., 2010; Glavovic et al., 2010). Incorporation of volcanic hazard and vulnerability information into land-use planning would lead to improvements in planning volcanic and risk reduction (Becker et al., 2010). Physical mitigation treatments such as the construction of hazard-resistant infrastructure designs can increase the resilience of infrastructure to volcanic hazard impacts. For example, the Agoyan hydroelectric power station located 5 km east of the city of Baños in Ecuador is occasionally exposed to lahars and has a specially designed floodgate system in place so that the intake flow can be diverted away from generation components (Sword-Daniels et al., 2011). Infrastructure operational plans, which include volcanic hazard response and clean-up actions, can also lead to increased resilience through preparedness (Wilson et al., 2014). To develop and implement mitigation strategies which increase resilience to volcanic hazards, infrastructure operators need comprehensive quantitative infrastructure vulnerability and risk advice; this thesis addresses these aspects.

1.4 Thesis aims and objectives

The primary aim of this thesis is to assess and quantify the vulnerability of critical infrastructure sectors to volcanic hazards. It is vital that critical infrastructure sectors remain operational and able to provide critical services to society during emergency response and recovery from a volcanic eruption. While the volcanological research community has a broad qualitative understanding of volcanic impacts to infrastructure, a detailed quantitative understanding is lacking in many instances. Quantitative infrastructure vulnerability assessments allow more robust, comparable and transparent risk assessments on which volcanic risk management and reduction decisions are made. My research builds on previous New Zealand and international studies and provides a greater quantitative understanding of infrastructure vulnerability to volcanic hazards, in particular tephra fall, the most common and widespread hazard, as part of quantitative volcanic risk management.

The primary aim of this thesis will be addressed in the following objectives:

1. Review and identify known impacts to critical infrastructure sectors from volcanic eruptions within the last 100 years (Chapter 2).
2. Identify volcanic hazard impact mechanisms and categorise infrastructure disruption and damage into standardised impact intensity classes (Chapter 2).
3. Develop a database to store volcanic impact data and facilitate the collection of standardised post-eruption impact data for future eruptions (Chapter 3).
4. Establish a methodological framework for the quantification of infrastructure vulnerability to volcanic hazards using vulnerability and fragility functions (Chapter 4).
5. Derive vulnerability and fragility functions for tephra fall impacts to critical infrastructure using the volcanic vulnerability framework (Chapter 4).
6. Utilise fragility functions to assess the tephra fall risk to the electrical transmission network in the North Island of New Zealand using a new probabilistic tephra fall hazard model (Chapters 5–6).

1.5 Thesis structure

The body of this thesis consists of five chapters comprising published, submitted or prepared manuscripts for scientific journals. A version of a published manuscript is contained in Chapter 2, which reviews known critical infrastructure impacts from historic volcanic eruptions. This chapter also identifies different impact mechanisms and defines impact intensity states for critical infrastructure sectors for four volcanic hazards (tephra fall, PDC, lahar, and lava flow). Chapter 3 presents a database which collates post-eruption impact data in a standardised format. This database, along with data collection guidelines, will facilitate the acquisition of post-eruption impact data following future volcanic eruptions. In Chapter 4 a framework is established to derive vulnerability and fragility functions for critical infrastructure impacts from volcanic hazards. The volcanic vulnerability framework details data, methodology and documentation requirements for functions. Fragility functions for electricity supply, water supply, wastewater, transportation and critical components to tephra fall impacts are developed. In Chapter 5, a probabilistic tephra fall hazard assessment for the North Island of New Zealand is undertaken to assess tephra thickness exceedance from six volcanoes. Chapter 6 presents a quantitative risk assessment of the electrical transmission network in the North Island of New Zealand, using the probabilistic tephra fall hazard assessment from Chapter 5 and the fragility functions derived in Chapter 4. Chapter 6 is intended for submission as a manuscript to a scientific journal and therefore there is some repetition of vulnerability material from Chapter 4. Finally, Chapter 7 concludes the thesis with a general summation of the main conclusions and highlights areas for further research.

The appendices contain supplementary material and research undertaken by and co-authors and me. Appendix A contains a review of existing volcanic fragility functions for critical infrastructure and is related to Chapter 4. Appendix B contains additional post-eruption infrastructure impact assessment guidelines from Chapter 3. Appendix C contains a submitted version of a co-authored GNS Science report documenting and analysing infrastructure, agriculture and human health impacts from the 14 February 2014 eruption of Mt. Kelud, Indonesia. This is included to show evidence of a post-eruption impact assessment by a collaborative research group.

The methodologies, applications and results described in the chapters are a direct result of my own research; however, several co-authors have made invaluable contributions. Their specific inputs are described in the signed co-authorship statement forms at the beginning of this thesis.

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Chapter Two – Volcanic hazard impacts to critical infrastructure: A review

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Journal of Volcanology and Geothermal Research 286, 148–182

Received: 15 July 2014

Accepted: 13 August 2014

Available online: 10 September 2014

2.1 Abstract

Effective natural hazard risk assessment requires the characterisation of both hazards and vulnerabilities of exposed elements. Volcanic hazard assessment is at an advanced state and is a considerable focus of volcanic scientific inquiry, whereas comprehensive vulnerability assessment is lacking. Cataloguing and analysing volcanic impacts provide insight on likely societal and physical vulnerabilities during future eruptions. This paper reviews documented disruption and physical damage of critical infrastructure elements resulting from four volcanic hazards (tephra fall, pyroclastic density currents, lava flows and lahars) of eruptions in the last 100 years. We define critical infrastructure as including energy sector infrastructure, water supply and wastewater networks,

transportation routes, communications, and critical components. Common trends of impacts and vulnerabilities are summarised, which can be used to assess and reduce volcanic risk for future eruptions. In general, tephra falls cause disruption to these infrastructure sectors, reducing their functionality, while flow hazards (pyroclastic density currents, lava flows and lahars) are more destructive causing considerable permanent damage. Volcanic risk assessment should include quantification of vulnerabilities and we challenge the volcanology community to address this through the implementation of a standardised vulnerability assessment methodology and the development and use of fragility functions, as has been successfully implemented in other natural hazard fields.

2.2 Introduction

The aim of natural hazard risk assessment is to evaluate the extent and nature of risk in a particular area by evaluating potential hazards that together could harm people, property and services (UNISDR, 2009). Risk assessments are an integral part of the risk management process (Figure 2.1) and comprise hazard, exposure and vulnerability assessments (Marzocchi et al., 2012). Recent natural disasters such as the Eyjafjallajökull eruption in Iceland (2010), the Tōhoku earthquake and tsunami in Japan (2011), Hurricane Sandy in the USA (2012) and Typhoon Haiyan in the Philippines (2013) highlight the need for effective natural hazard risk management and sustainable development (UNISDR, 2014). Various studies have identified society's increasing vulnerability to disasters as a consequence of population expansion in hazardous areas and increasing economic and environmental strain (Rougier et al., 2013). Risk assessment and management is essential for identifying, avoiding and minimising losses associated with natural hazard impacts. Using quantitative risk assessment provides a numerical estimation of risk which can facilitate comparisons between different natural hazards and locations and allow prioritisation of risk mitigation strategies to increase society's resilience to these hazards. Risk mitigation strategies can be broadly classified as:

- Land-use planning (citing) used to decrease exposure of people, buildings and infrastructure to natural hazards.
- System and component design to improve resilience if exposed to natural hazards.
- Contingency planning (i.e., preparedness and response) used to reduce the impacts of natural hazards and decrease restoration and recovery times.

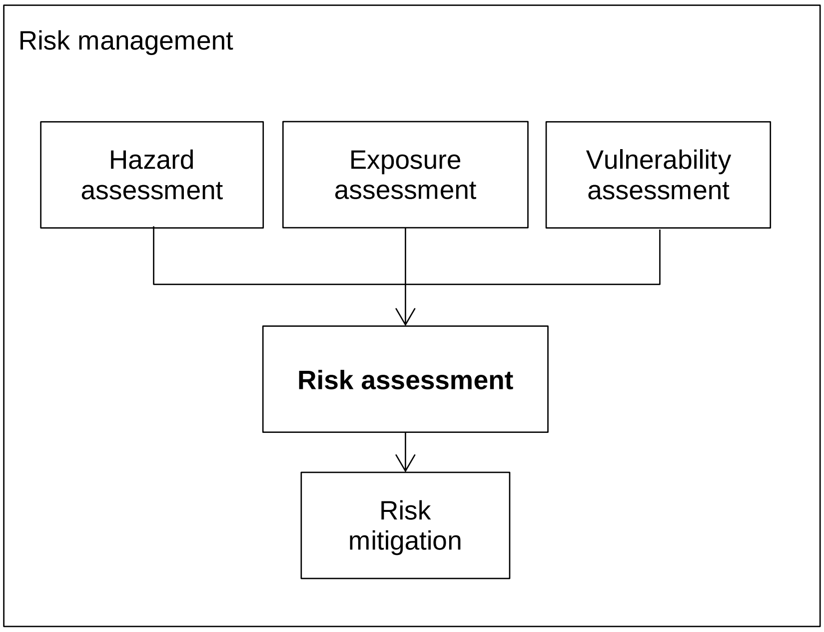


Figure 2.1: Schematic description of components and process followed during natural hazard risk management.

A challenge for volcanic risk assessment is the multi-hazard characteristic of volcanic eruptions (Sparks et al., 2013). Tephra falls, pyroclastic density currents (PDCs), lava flows and lahars can occur simultaneously or sequentially and over differing spatial and temporal scales, potentially adversely affecting society (see Table 2.1 for hazard descriptions). The threat to society is considerable: there are at least ~600 million people living in areas that could be affected by volcanic eruptions (Auker et al., 2013). As populations increase in volcanically active areas, exposure and vulnerability to volcanic hazards will increase (Chester et al., 2000). However, pre-emptive hazard assessment, volcanic monitoring, early warning, crisis management and other mitigative strategies can reduce the impact on society (Sparks et al., 2013). For example, the number of likely fatalities was reduced by two orders of magnitude during the 1991 eruption of Mt. Pinatubo, Philippines when thousands of people were evacuated prior to the climactic eruption (Sparks et al., 2013). The death toll since 1900 CE from volcanic eruptions is small compared to other natural hazards; for example, in that time period there were ~280,000 fatalities from volcanic eruptions (Auker et al., 2013) compared to >2 million from earthquakes (Holzer and Savage, 2013). However, disruption, damage and economic loss from volcanic eruptions is considerable, although hard to quantify (Sparks et al., 2013). One aspect of modern society that is commonly and sometimes severely disrupted and damaged by volcanic hazards is critical infrastructure (Blong, 1984; T.M. Wilson et al., 2012), the focus of this paper. Critical infrastructure is defined as a network of man-made systems and processes that function collaboratively to produce and distribute essential goods and services (Rinaldi et al., 2001) which are heavily relied upon by society for daily function (Dunn et al., 2013). Critical infrastructure discussed here includes electrical supply networks, water and wastewater networks, terrestrial transportation networks and communications. We also consider buildings, heating, ventilation and air conditioning (HVAC) systems and electronic equipment common to all infrastructure sectors. There has been a lack of systematic, quantitative collection and reporting of impacts to critical infrastructure, which has hindered quantitative risk assessment.

In this review we build an evidence base of disruption and direct damage to critical infrastructure sectors from tephra falls, PDCs, lava flows and lahars, and distil common impact trends to contribute to improved quantitative volcanic risk assessment. Section 2 of this paper places this review in the context of natural hazard risk assessment and summarises physical vulnerability assessments in volcanology and other natural hazards while also highlighting some of the challenges faced with adoption of robust quantitative volcanic vulnerability assessment. Section 2.4 summarises current knowledge of physical impacts to critical infrastructure from volcanic hazards highlighting vulnerable infrastructure components and impact mechanisms from a range of international case studies. In Section 2.5 we discuss general trends in impact severity and at which hazard intensities disruption and damage may be likely to occur for each hazard. We also provide an approach to estimate vulnerability with impact states and fragility functions. We conclude in Section 2.6 with a discussion of future directions for continued development of quantitative physical vulnerability assessment with the goal to improve volcanic risk assessment. Definitions of terms used throughout this review are in Table 2.2.

Table 2.1: Description of hazard origin, transport, composition, primary damaging characteristics and common hazard intensity metrics for tephra falls, pyroclastic density currents (PDCs), lava flows and lahars.

Hazard	Hazard characteristics	Primary damaging characteristics	Hazard intensity metric (HIM) definitions
Tephra fall	*Origin:* explosive volcanic eruptions or fire fountaining as a result of magma fragmentation. *Transport:* dispersed in convective eruption plumes up to 40–50 km vertically and thousands of kilometres laterally.[a, b, c] *Composition:* vitric (volcanic glass), crystalline and/or lithic particles. Blocks and bombs (>64 mm in diameter), lapilli (2–64 mm) and ash (<2 mm).[d]	*Loading:* relates tephra thickness and bulk density. Increased loading leads to structural damage of buildings and infrastructure.[e] *Thickness:* similar to loading and generally decreases exponentially with distance from the vent.[f] *Dispersal:* tephra can be dispersed over wide extents. Tephra deposits may be eroded and remobilised by wind and/or water for long periods post-eruption.[g] *Grainsize:* smaller particles are dispersed further from the vent and can penetrate smaller openings than larger particles. *Surface chemistry:* tephra particles have surface coatings of soluble salts as a result of scavenging in volcanic plumes[h]. Salts may be released upon contact with water, resulting in water contamination.[i] Acidic coatings may cause corrosion of metals.[j] *Abrasiveness:* tephra is highly abrasive due to the hardness and angular morphology of individual particles.[k]	*Thickness (common unit: mm):* accumulated thickness of tephra fall. *Static load (common units: kg/m^2, kPa):* mass of tephra per unit area on a surface. Indicates load on an object in the vertical direction. *Particle density (common unit: kg/m^3):* the density of individual particles influences their mobility and settling rate in liquids. *Surface chemistry (common unit: mg/kg dry weight for individual elements):* concentration of soluble salts on the surface of tephra particles. *Grainsize:* particle size distribution of tephra at a particular site. *Moisture content (common unit: vol. %):* water content of tephra deposit. Influenced by plume dynamics, environmental conditions during and subsequent to deposition. *Hardness:* particle hardness influences abrasiveness of tephra deposits. *Atmospheric concentration (common unit: µg/m^3):* concentration of tephra particles suspended in air. Is relevant for aircraft safety, visibility and health.

Hazard	Hazard characteristics	Primary damaging characteristics	Hazard intensity metric (HIM) definitions
PDC	*Origin:* (1) collapse of an unstable eruption column, (2) directed blast, (3) low pyroclastic fountaining, and (4) lava dome collapse.[b, l, m] *Transport:* gravity-driven flows which accelerate down slope at velocities up to 300 m/s[n] and travel distances of tens of kilometres.[o] *Composition:* mixtures of generally hot volcanic ejecta and gas.[p]	*Dynamic pressure:* relate the flows density to its velocity. Dynamic pressures can be on the order of tens of kilopascals[q] enough to damage or destroy buildings and infrastructure. *Run-out distance:* PDCs can flow distances of tens of kilometres, are generally confined to valleys[o], although overtopping can unpredictably occur.[m] *Temperature:* may reach 1100°C[m], sufficient to burn common building materials.[r] *Abrasiveness:* pyroclastic material is highly abrasive and in combination with high flow velocity can cause significant abrasion to impacted surfaces.	*Dynamic pressure (common unit: kPa):* the kinetic energy per unit volume of the flow which changes with flow density and velocity. Used to infer lateral impacts. *Velocity (common unit: ms^{-1}):* velocity of the PDC during emplacement. Can be used instead of dynamic pressure if PDC density is unknown. *Temperature (common unit: °C):* temperature of the PDC at emplacement. *Thickness of deposit (common unit: mm):* thickness of the PDC deposit after emplacement has ceased.
Lava flow	*Origin:* outpourings of molten rock from volcanic vents or fissures. *Transport:* flows emplaced as a dynamically continuous unit elongated downslope. Lengths are typically <10 km and velocities ~10's km/hr, although higher velocities are documented.[s] *Composition:* the majority of flows are basaltic in	*Morphology:* flows tend to travel along confined paths as cohesive, sometimes massive, units (10's m thick) which impact and inundate objects in the flow path. Flows solidify on cooling. *Temperature:* are between 800–1200°C[s] during eruption, sufficient to ignite fires.	*Presence of lava:* whether lava is present at a particular location, regardless of flow depth. *Depth of flow (common unit: mm):* depth of the solidified lava flow. *Dynamic pressure (common unit: kPa):* the kinetic energy per unit volume of the flow which changes with flow density and velocity. Used to infer lateral impacts. *Velocity (common unit: m/s):* velocity of the lava flow during emplacement. Can be used instead of dynamic pressure if flow density is unknown.

Hazard	Hazard characteristics	Primary damaging characteristics	Hazard intensity metric (HIM) definitions
	composition although high silica and non-silicate flows occur.[s, t]		*Temperature (common unit: °C):* temperature of the flow. Ambient temperature around flow margins is equally important for infrastructure damage considerations. *Cooling duration (common units: hours, days):* time take for lava flow to cool sufficiently to reinstate infrastructure on top of flow.
Lahar	*Origin:* (1) eruption of hot pyroclastic material onto ice or snow, (2) eruptions through crater lakes, (3) breakout of crater lakes or other water bodies, and (4) rainfall after eruptions of voluminous tephra.[u] *Transport:* gravity-driven flows which travel down slope at velocities of 10's m/s and travel 10's km.[b] *Composition:* slurry of volcaniclastic material (i.e., tephra) and water other than normal streamflow.[v]	*Velocity:* can travel at high velocities which can partially damage or destroy buildings and infrastructure in flow path. *Erosive:* commonly erosive which can destabilise structures (e.g., bridge piers and abutments) located in or near to flow channels. *Run-out distance:* can travel for long distances and inundate large areas. *Depth:* commonly up to tens of meters in valleys and thin veneers outside of valleys[w] which is sufficient to bury infrastructure and sometimes inundate buildings and structure. *Temporal:* lahars may occur post eruption ("secondary") for many years as rain remobilises pyroclastic material, prolonging hazard impact.[x]	*Dynamic pressure (common unit: kPa):* the kinetic energy per unit volume of the flow which changes with flow density and velocity. Used to infer lateral impacts. *Velocity (common unit: ms^{-1}):* velocity of the lahar during emplacement. Can be used instead of dynamic pressure if lahar density is unknown. *Thickness of deposit (common unit: mm):* thickness of the lahar deposit remaining after emplacement. *Depth of flow (common unit: mm):* depth of the lahar during emplacement. Depth of flow can be greater than deposit thickness.

[a] Carey and Bursik (2000); [b] Parfitt and Wilson (2008); [c] Lockwood and Hazlett (2010); [d] Cashman et al. (2000); [e] Spence et al. (1996); [f] Johnston (1997); [g] Wilson et al. (2011); [h] Óskarsson (1980); [i] Witham et al. (2005); [j] Oze et al. (2013); [k] T.M. Wilson et al. (2012); [l] Branney and Kokelaar (2002); [m] Nakada (2000); [n] Wilson and Houghton (2000); [o] Valentine and Fisher (2000); [p] Burgisser and Bergantz (2002); [q] Clarke and Voight (2000); [r] Blong (1984); [s] Kilburn (2000); [t] Griffiths (2000).; [v] Smith and Fritz (1989); [u] Waitt (2013); [w] Vallance (2000); [x] Gran et al. (2011).

Table 2.2: Definitions of terms used throughout this review.

Term	Definition	Reference
Natural hazard	A dangerous natural phenomenon that may cause loss of life, property damage and disruption.	UNISDR (2009)
Exposure	People, property, systems and other elements present in the hazard zone that are subject to potential loss.	UNISDR (2009)
Vulnerability	The characteristic of an element that makes it susceptible to the effects of a hazard.	UNISDR (2009)
Risk	The combination of the probability of an event and its negative consequences.	UNISDR (2009)
Risk assessment	A methodology to determine the nature and extent of risk.	UNISDR (2009)
Risk management	The systematic approach of managing uncertainty and minimizing potential loss through the implementation of mitigation strategies.	UNISDR (2009)
Resilience	The ability of a system to absorb and recovery from the effects of a hazard.	UNISDR (2009)
Critical infrastructure	A network of man-made systems and processes that function collaboratively to produce and distribute essential goods and services. Sectors include: electrical supply networks, water and wastewater networks, transportation routes, communications, electronics and air conditioning.	Rinaldi et al. (2001)
Impact	Adverse consequence of hazards on the exposed asset.	Jenkins et al. (2014b)
Impact mechanism	The different methods by which a natural hazard can impact infrastructure.	This paper
Impact severity	The relative level of damage to elements.	This paper
Disruption	Impact caused to infrastructure prior to the onset of physical damage.	This paper
Physical damage	General term to describe damage to infrastructure causing complete loss of function until repair or replacement is undertaken.	This paper
Hazard intensity	The magnitude of a hazard at a particular site. We use the terms “low” and “high” to describe the end members of hazard intensity.	This paper
Hazard intensity metric (HIM)	Different hazard properties which can impact infrastructure. These properties can be measured and are related to the level of impact.	This paper
Fragility function	Equations which express the probability of differing levels of damage sustained for different infrastructure as a function of hazard intensity.	Rossetto et al. (2013)

Mitigation	The lessening of the adverse impacts of hazards through policy or structural strategies.	UNISDR (2009)

2.3 Natural hazard risk assessment

Natural hazard risk assessments combine hazard, exposure, vulnerability assessments (Figure 2.1) in order to determine the risk posed to a site, area or region from single- or multi-hazard source. Risk assessment informs the development of mitigation strategies and effective risk management, reducing loss and increasing resilience (Papathoma-Köhle et al., 2011). We provide a brief description of these assessments and refer the reader to Rougier et al. (2013) and Smith (2013) for in-depth reviews of natural hazard and risk assessments.

Hazard assessment procedures are similar for all natural hazards and concern determining hazard occurrence frequency, the spatial extent (hazard footprint) and hazard intensities (e.g., tephra thickness) within the hazard footprint (Smith, 2013). Deterministic (scenario-based) or probabilistic (range of scenarios) hazard models are used, the choice of which is determined by data availability and the type of assessment required (Panza et al., 2011). Hazard assessment outputs are commonly in the form of hazard maps which show hazard intensity as a function of spatial extent or hazard curves which show exceedance probability of certain hazard intensities at a given location. Exposure assessments identify the number, typology and location of elements (e.g., buildings, infrastructure and people) which have the potential to be impacted by the hazard(s) of interest. Exposure assessments can be at any scale, from site specific to regional, although an inverse relationship generally exists between level of detail and spatial scale. These assessments commonly make use of existing asset inventory data sets (e.g., asset databases held by local and regional authorities: Schmidt et al., 2011), although project specific data sets may be obtained through field investigation or remote sensing (e.g., Foulser-Piggott et al., 2014; Jenkins et al., 2014a). Vulnerability assessments are concerned with the consequences of natural hazard impacts on exposed elements and may be undertaken in physical, economic and/or social contexts (Fuchs et al., 2012) (see Section 2.3.1 for a detailed discussion).

Risk assessments are the combination of hazard, exposure and vulnerability assessments (Figure 2.1) and determine the nature and extent of risk to a site, area or region of interest. Assessments can be qualitative (descriptive data) or quantitative (measurable data) or a combination of both, depending on the nature of available data and the purpose of the assessment (Jelínek et al., 2012). If possible, quantitative assessments are preferred because they can facilitate a more precise comparison between risks, although results can be expressed using qualitative descriptions such as ‘high’, ‘medium’ or ‘low’ risk (Jelínek et al., 2012) to facilitate effective communication (Uzielli et al., 2008). There is increasing use of multi-hazard risk assessment (e.g., Schneider and Schauer, 2006; Schmidt et al., 2011; Marzocchi et al., 2012; UNISDR, 2013) for particular sites or regions that may be impacted by more than one natural hazard as the combined effect of all hazards influences risk (Zuccaro et al., 2008). Hazard, exposure and vulnerability assessments for each hazard are combined to create a multi-hazard risk index or ranking for a particular area (Marzocchi et al., 2012).

While in theory both hazard and vulnerability aspects of risk assessment should be advanced to the same level of detail, there is often discrepancy between the two, notably for volcanic hazards (Sparks et al., 2013). Quantitative assessments of various volcanic hazards and their processes are well advanced (e.g., Bonadonna, 2006; Wadge, 2009; Jenkins et al., 2012), with fieldwork, laboratory studies and numerical models providing qualitative outputs for the spatial and temporal extent and intensities of hazards, while taking into account uncertainties. Vulnerability assessments are less advanced. For tephra fall and PDC there has been steady progress in qualitative understanding of vulnerability for structures, agriculture and some critical infrastructure, however quantitative assessment of vulnerability over a range of hazard intensities is more sparse. This lack of comprehensive understanding can preclude robust quantitative volcanic risk assessment (T.M. Wilson et al., 2012; Jenkins et al., 2014a). Despite this, risk assessment methodologies have been developed to assess volcanic risk to infrastructure. For example, the Auckland Engineering Lifelines Project (Daly and Wilkie, 1999; Daly and Johnston, 2015) developed a methodology using deterministic volcanic hazard scenarios and qualitative descriptions of impact type and likelihood as the basis for volcanic risk assessment in Auckland, New Zealand. This project set the groundwork for the development of subsequent volcanic management initiatives (Auckland Lifelines Group, the Volcanic Impacts Study Group and the Auckland Science Advisory Group) and research programmes (e.g., DEVORA, 2015) (Daly and Johnston, 2015) as well as for this paper.

2.3.1 Natural hazard vulnerability assessments

There are different types of vulnerability (e.g., physical, social, economic; see Fuchs et al., 2012); in this paper we restrict our focus to physical vulnerability, that is the susceptibility of an infrastructure system or component to impact from a natural hazard. There are three main approaches for physical vulnerability assessment: the use of vulnerability indicators, damage matrices, and fragility or vulnerability functions (Kappes et al., 2012). Figure 2.2 briefly summarises these approaches and provides examples of when they may be used in volcanic vulnerability assessment.

Data for deriving physical vulnerability assessments come from empirical, analytical, expert judgment, and hybrid sources (Rossetto and Elnashai, 2003). Table 2.3 presents some of the advantages and disadvantages of each approach. The most common data source for all natural hazards, including volcanic eruptions, is observational (empirical) data collected during or immediately after a hazardous event. These data are generally scarce due to the danger and limited access in impacted zones, the expense of collecting such data and the infrequent nature of some hazards (Jenkins et al., 2014a), although remote sensing techniques allow data collection in hazardous areas (e.g., Sanyal and Lu, 2005; Mas et al., 2012; Dong and Shan, 2013; Jenkins et al., 2014a). The advantage of empirical data is that a range of hazard intensities and exposed element properties are taken into account, which are often difficult to include in models. Empirical data can also be used to confirm and calibrate other data sources and assessments (e.g., Turner et al., 2013), although this is unfortunately rare (Rossetto and Elnashai, 2003). In the absence of empirical data, other forms of data such as analytical (experimental), expert judgement or hybrid combinations can be sought (Table 2.3).

Vulnerability approach example	Description

Population exposure index	Volcanic hazard level 1 (low)	2	3 (high)
0-0.5	1	1	1
1	1	2	2
1.5	1	2	3
2	2	2	3
2.5-3	2	3	3

Vulnerability indicator

- Vulnerability indicators or indices represent a property of a system and provide information regarding its susceptibility to natural hazard(s) impacts (Birkmann, 2006; Kappes et al., 2012).
- Widely used in social sciences, but less common in physical vulnerability assessment due to difficulties in applicability of indicators to characterise a large spectrum of hazards (Kappes et al., 2012).

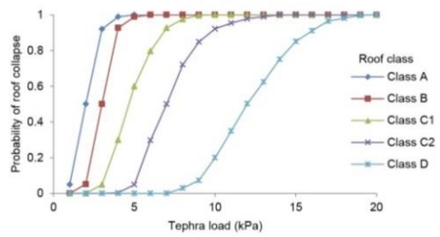
Example:
Vulnerability indices (coloured squares) for developing countries based upon volcanic hazard level and population exposure. From Aspinall et al. (2011).

Damage level	PDC intensity 4 kPa	6 kPa	8 kPa	10 kPa
D0	0.0	0.00.1	0.0	0.0
D1	0.1	0.2	0.0	0.0
D2	0.19	0.13	0.0	0.0
D3	0.28	0.31	0.0	0.0
D4	0.3	0.31	0.1	0.0
D5	0.15	0.54	0.9	1.0

Damage matrix

- Define the probability of a specific damage level being reached for a infrastructure element at a specific hazard intensity level (Menoni, 2006; Kappes et al., 2012; Rossetto et al., 2013).
- Matrices may only provide data for specific regions where elements fit defined vulnerability classes, limiting their wide applicability.
- Used when infrastructure damage can be easily assigned to a damage level and specific hazard intensity.

Example:
Probability of European building class A being at a specific damage level for a specific PDC intensity. D0-no damage, D5-complete damage. From Zuccaro et al. (2008).



Fragility function

- Quantitatively estimates the probability of a damage state being exceedance as a function of hazard intensity.
- Used when there is sufficient hazard intensity data for all damage states.
- Requires large statistically valid data sets.

Example:
Probability of reaching partial or total roof collapse (damage state D5) as a function of tephra load for European roofs (reprinted from Zuccaro et al. (2008) with permission from Elsevier).

Figure 2.2: Graphical representation and descriptions of the three most common approaches to assess natural hazard vulnerability: vulnerability indicators (Aspinall et al., 2011); damage matrices and fragility functions (Zuccaro et al., 2008).

A quick note on risk assessment in other natural hazard fields is warranted to place volcanic risk assessment in context. Earthquake risk assessment has well established quantitative vulnerability assessments that estimate damage, disruption and casualty impacts (Reitherman, 2012), which has informed establishment of robust seismic building codes; pioneering work began in the 1980s focusing on seismic safety of nuclear power plants (e.g., Kennedy et al., 1980; Kennedy and Ravindra, 1984). The field has well-established methods for post-earthquake building assessments (Rossetto et al., 2010) and for deriving fragility functions to probabilistically estimate structural damage (Porter et al., 2007). Other natural hazard fields employ similar empirical approaches to earthquake vulnerability assessment but are less well defined. Analytical modelling approaches are also used to develop fragility functions (e.g., Vaidogas and Juocevičius, 2008; Koshimura et al., 2009; Quan Luna et al., 2011). As a field, volcanology trails behind earthquake risk assessments but is on par with landslide and tsunami risk assessment.

Table 2.3: Advantages and disadvantages of the different methodological approaches used to develop fragility and vulnerability functions in natural hazard vulnerability assessment (modified from Schultz et al., 2010).

Approach	Data	Advantages	Disadvantages
Empirical	Controlled experiments Post-event damage assessment	Repeatable experiments Range of hazard and infrastructure characteristics taken into account	Difficulties in replicating natural hazards in laboratory Site, region, structure specific Scarce data of variable quality
Judgement -based	Expert elicitation	Assess wide range of impacts, some of which have not been previously observed Not limited by impact data or models Can be used to refine other functions	Quality depends on expert's expertise and subjectivity Can be difficult to validate Differing and contradictory opinions
Analytical	Numerical modelling	Increased reliability and repeatability and reduced bias Can be extrapolated to new situations	Substantial computation Based on simplifications and assumptions
Hybrid	Combination of different approaches	Reduce limitations by combining different approaches Reduce uncertainties in functions	Limitations are the same as individual approaches

2.3.2 Volcanic perspective on vulnerability assessments

Volcanic risk assessment has typically focused on loss of life and therefore physical vulnerability assessments have primarily targeted building damage and occupant exposure with limited analysis of other physical societally-relevant assets such as critical infrastructure.

2.3.2.1 Data sources

Observational data is the key data set for modern volcano risk assessment, and began in earnest with observations in the aftermath of the 1980 eruption of Mt. St. Helens, USA which affected critical infrastructure, health and economic activities across Washington (Lipman and Mullineaux, 1981). A formative review of the effects of volcanic eruptions is presented by Blong (1984), who documents a wide range of volcanic hazard impacts on buildings, infrastructure, agriculture, economy and people. The Blong (1984) review is a significant contribution to the field and is the basis for current understanding of impacts to the built environment and still relied upon heavily today. Since the eruption of Mt. St. Helens, field observations following eruptions from Mt. Pinatubo in 1991 (e.g., tephra-induced building damage; Spence et al., 1996), Rabaul in 1994 (e.g., tephra-induced building damage; Blong, 2003a), Montserrat in 1997 (e.g., PDC-induced building damage; Baxter et al., 2005), Merapi in 2010 (e.g., PDC-induced building and infrastructure damage; Jenkins et al., 2013) and other case studies (e.g., T.M. Wilson et al., 2012; Jenkins et al., 2014a) have strengthened the knowledge regarding volcanic impacts to society, particularly around building damage and occupant safety. In order to continue collecting high quality empirical data Jenkins et al. (2014a) proposes a standardised physical vulnerability survey methodology detailing minimum data requirements to ensure quantifiable data collection.

Where observational data are lacking, experimental assessment (e.g., Spence et al., 2004a; Zuccaro et al., 2008; Wardman et al., 2012c) have been used to estimate vulnerability. Experimental data are sparse due to difficulties accurately replicating some volcanic hazard properties in the laboratory (Jenkins et al., 2014a). Theoretical calculations (e.g., Petrazzuoli and Zuccaro, 2004; Jenkins et al., 2013) and expert elicitation (e.g., Coppersmith et al., 2009; Aspinall and Cooke, 2013) can also be used to produce both qualitative and quantitative vulnerability assessments that can be applied to a range of element typology and hazard properties.

2.3.2.2 Quantifying vulnerability

Quantifying vulnerability of buildings is more common within the literature as volcanic risk assessment is primarily concerned with loss of life. Jenkins et al. (2014b) suggest that vulnerability assessments of buildings can also be undertaken to: (1) identify buildings that may benefit from mitigation measures; (2) quantify potential damage and loss of buildings following successful evacuation; and (3) support development of improved construction guidelines for new buildings. As such, numerous studies (Spence et al., 2005; Spence et al., 2007; Marti et al., 2008; Zuccaro et al., 2008) and field observations (Spence et al., 1996; Baxter et al., 2005; Jenkins et al., 2013) have quantitatively estimated building vulnerability for volcanic hazards, particularly tephra falls and PDCs. The outputs of these studies are similar to those of earthquake risk assessment and describe building damage as a function of hazard intensity using hazard intensity thresholds, damage matrices and fragility and vulnerability functions. See Appendix A for a brief review of fragility and vulnerability functions derived for volcanic hazards. The majority of these studies have assessed vulnerability to European buildings with a large focus on buildings in Naples, Italy and those surrounding Mt. Vesuvius. The primary reason for the focus on these buildings is because there is a large population living close to or on the flanks of one of the most dangerous volcanoes in the world (Baxter et al., 2008). As such, these assessments apply only to European building typologies would need to be re-evaluated and refined for other areas of interest.

In contrast, vulnerability assessment for critical infrastructure systems and components is not well established, with the majority of assessments qualitative in nature (e.g., Patterson, 1987; Johnston and Nairn, 1993; Daly and Wilkie, 1999). However, damage or disruption to critical infrastructure is likely to have a higher magnitude impact on society than building damage (Jenkins et al., 2014a) due to the interconnectedness of these infrastructure (T.M. Wilson et al., 2012). The New Zealand Volcanic Impacts Study Group (NZ VISG) has over the past 15–20 years systematically assessed tephra fall impacts to critical infrastructure through post eruption impact assessment and semi-structure interviews with critical infrastructure managers (T.M. Wilson et al., 2012; Wilson et al., 2014). These studies (e.g., T.M. Wilson et al., 2012) have built on early New Zealand volcanic vulnerability studies (e.g., Patterson, 1987; Johnston and Nairn, 1993; Daly and Wilkie, 1999) and provide a large amount of qualitative data describing the likely impacts and points of vulnerability for each critical infrastructure sector as a result of tephra fall. Some studies have attempted to quantitatively relate infrastructure disruption and damage to hazard intensity using intensity thresholds (e.g., Jenkins et al., 2014b) and fragility functions (Table 2.4 and Appendix A). However, these quantitative relationships have been based on few empirical data and therefore are associated with sizeable uncertainty. There is a need to refine infrastructure vulnerability estimates for tephra fall and volcanic flow hazards in order to have robust volcanic risk assessments, hence the need for this review and continued and standardised research in this field.

Table 2.4: Existing critical infrastructure fragility and vulnerability functions developed for different volcanic hazards. We found no published peer-reviewed fragility functions for water supply, communication networks or lava flows. See Appendix A for a review of these functions.

Infrastructure sector	Tephra fall	PDC	Lahar
Electrical supply	a		
Wastewater networks	b		
Transportation networks	b		
Buildings	b, c, d, e, f	d, g, h	g
Critical components	i		

[a] Wardman et al. (2012c); [b] Kaye (2007); [c] Spence et al. (2005); [d] Zuccaro et al. (2008); [e] Jenkins and Spence (2009); [f] Maqsood et al. (2014); [g] Zuccaro and De Gregorio (2013); [h] Spence et al. (2007); [i] G. Wilson et al. (2012).

2.3.2.3 Challenges in assessing physical vulnerability

There are a number of aspects when assessing physical vulnerability in regards to volcanic hazards which make fully-quantitative approaches difficult to achieve. Douglas (2007) attributed this to a number of challenges, including:

- Volcanic eruptions are multi-hazard events and therefore critical infrastructure sites can by impacted by multiple sequential or simultaneous hazards. This can lead to a range of different impact mechanisms to be considered, again adding complexity.
- Individual volcanic hazards can cause different types of damage to the same asset depending on the hazard properties. For example, tephra fall can damage a metal roof by increasing the static load causing it to collapse, in addition to damaging it through corrosion and abrasion.
- There are no widely adopted volcanic building codes or building performance guidelines which regulate infrastructure design in volcanic hazard zones and prompt vulnerability assessment and fragility function development.
- There is a diverse range of infrastructure system design, configuration and components which make it difficult to assign generic vulnerability assessments for all infrastructure sectors.
- Time scales leading up to volcanic eruptions can be long compared to earthquakes (discrete events). Long eruption lead up times can allow pre-event warnings, resulting in evacuations which remove the danger to life. Given the focus on loss of life vulnerabilities, the mitigative measure of mandatory, encouraged, or self-evacuations reduce social pressure to evaluate building fragility.
- Volcanic episodes with multiple hazardous events can take place over a long time, adding complexity to vulnerability assessments.
- Difficulties in accurately measuring hazard intensity (e.g., bulk densities of lahars, dynamic pressures of PDCs, tephra thickness). Often PDC and lahar

parameters are inferred from deposits due to personal safety concerns and destruction of measuring instruments during flow emplacement. Deposits, especially tephra fall, may be reworked by erosional processes and thus incorrectly measured (Engwell et al., 2013).

- Volcanic eruptions are infrequent events, resulting in a lack of quantitative observational impact data. Volcanic post event assessments are primarily focused on the hazard itself and not the impacts.

2.4 Historically observed impacts to critical infrastructure

In order to estimate vulnerability to critical infrastructure during future eruptions, insights can be gained from analysing past impacts. In this section we review the literature to provide a semi-qualitative overview of disruption and damage to critical infrastructure by volcanic hazards. We consider impacts from tephra falls, PDCs, lava flows and lahars (see Table 2.1 for hazard descriptions) to electrical supply networks, water supply and wastewater networks, terrestrial transportation networks, communications, computers and air conditioning. As buildings and critical components (HVAC and electronic equipment) are widely used as key components in each infrastructure sector we finish with a dedicated section for critical components and building impacts (Section 2.4.6 and 2.4.7, respectively). Table 2.5 tabulates documented impact occurrence per decade for the past century for each infrastructure sector indicating the prevalence and occurrence of impacts over time. Table 2.6 summarises impacts to critical infrastructure from recent eruptions in New Zealand to provide context for Chapters 5 and 6. Table 2.7 summarises the main vulnerabilities for each infrastructure sector and summarises mitigation actions based on site exclusion, infrastructure design and operation and response planning.

Table 2.5: Summary table of documented volcanic impacts to critical infrastructure grouped by decade indicating the prevalence and occurrence of impacts over time. Symbols are: × Pre 1980s; # 1980s; * 1990s; § 2000s; and + 2010s.

Sector	Impact	Tephra falls	PDCs	Lava flows	Lahars
Electrical supply	Flashover	# * § +			
	Abrasion – dry	# +			
	Abrasion – wet	*			*
	Corrosion	+			
	Gravel contamination	+			
	Physical damage to lines	§	§	× §	§
Water supply network	Pump, motor abrasion	# * +			
	Pipe, channel blockage	× # * +			× *
	Pipe ruptures		* §	× §	§
	Intake & filter blockages	× * +			×
	Water quality decrease	× # § +		§	
	Water shortages	× *			
Wastewater network	Pump, motor abrasion	× #			
	Pipe blockage	× # §			
	Infill of tanks	§ +			
	Filter blockage	§			
	Treatment disruption	# §			
Transportation	Road damage		# §	× # §	# * +
	Road burial/closure	* § +	§	# §	+
	Vehicle damage	# * § +	# *	#	× #
	Traction/visibility reduction	# * § +		#	
	Airport closure or damage	× # * +	*	§	§
	Aircraft damage	× # * +			
	Railway closure or	× # +		× #	× #

Sector	Impact	Tephra falls	PDCs	Lava flows	Lahars
	damage				
	Port closure or damage	× +		×	
	Ship damage	§	×		
Communication	Physical damage	# §	*		
	Signal interference	# * § +			
Buildings	Lateral impact damage		× # * § +	× # * §	# * § +
	Roof damage/ collapse	* § +	#		
	Fire		× * +	# §	
	Corrosion	*			
	Gutter damage	* §			
	Burial	× §	# §	× # §	# *
Critical components	Computer damage	# §			+
	HVAC damage	*			

Table 2.6: Summary of critical infrastructure impacts from recent New Zealand eruptions.

Volcano	Eruption year	Description of impacts	References
Mt. Tarawera	1886	Thick tephra and mud deposits collapsed roofs and destroyed buildings in villages surrounding the volcano.	Smith (1886); Blong (1984)
Mt. Ruapehu	1945	Prolonged eruptions produced tephra over the North Island causing reduced visibility on roads (primary and remobilised tephra fall), contaminated tank water supplies, blockage of water filters, difficulties in pumping water and disrupting electrical supply to the Chateau Tongariro at the base of the volcano.	Johnston (1997)
	1953	Lahar weakened the Tangiwai rail bridge which collapsed when the train crossed killing 151 people.	O'Shea (1954)
	1969	Lahars damaged and infilled a ski field building on the volcano. The eruption blast destroyed Dome Shelter and its near the vent. Tephra increased turbidity and caused water contamination in	Collins (1978); Mazey (1978); Traill (1978); Johnston (1997)

Volcano	Eruption year	Description of impacts	References
		Whakapapa and Iwikau villages. Wastewater treatment at Whakapapa was disrupted. Tephra caused corrosion of roof paint.	
	1975	The eruption severely damaged Dome Shelter and Glacier Hut was damaged by ballistics. Lahars destroyed a ski field building, damaged ski lift foundations, washed away two small pedestrian foot bridges, overtopped State Highway 48 and filled the tunnel and aqueduct of the Tongariro Power Development Scheme which was still under construction.	Nairn et al. (1979)
	1995–96	Lahars destroyed a footbridge, caused damage to an aqueduct access ford. Remobilisation of tephra and secondary lahars caused significant and ongoing abrasion damage to the turbines at the Rangipo Power Station causing approximately 15 years of wear in seven months. The turbines were shut down and repaired. Tephra fall caused widespread disruption to aviation due to airspace restrictions and closure of airports across the North Island. During and after tephra falls visibility on roads was reduced and roads were closed. Tephra caused insulator flashover on high voltage transmission lines at the base of the volcano with tephra being cleaned manually. Tephra caused damage to roof paint and gutter systems. Some ski lift towers on the volcano suffered corrosion damage.	Johnston (1997); Johnston et al. (2000)
Tongariro	2012	The Tongariro Alpine Crossing track was damaged by ballistics and pyroclastic surge. Ballistics also caused damage to a hut. Tephra fall caused a short duration closure of the Rangipo Power Station as a precaution. There were no impacts to the transmission lines surrounding the volcano. State Highways 1 and 46 were closed due to low visibility. Some flight delays at Napier Airport due to trace tephra. Rangipo Prison water supply automatically shutdown due to increased turbidity.	Leonard et al. (2014)

Table 2.7: Summary of the main vulnerabilities for critical infrastructure sectors for impacts from tephra falls, PDCs, lava flows and lahars and whether impacts can be mitigated by site exclusion (avoidance), physical design of infrastructure or response and operational planning.

Infrastructure sector	Hazard			
	Tephra fall	PDC	Lava flow	Lahar
Electrical supply	*Vulnerability:* Flashover of insulators, abrasion of HEP turbines, line breakage, tephra ingress into critical equipment. *Site exclusion:*[a] No *Design:*[b] Increase insulation and use of anti-pollution strategies to minimise flashover. Strengthen structures or use tephra shedding designs to minimise tephra loading. Increase system redundancy. *Contingency planning:*[c] Tephra clean-up operations and methods. Use of backup generators.	*Vulnerability:* Breakage of towers, poles and lines, damage to other structures, abrasion of HEP turbines. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow paths. *Design:* Strengthen some structures if possible. Locating services underground. *Contingency planning:* Clean-up operations and methods.	*Vulnerability:* Breakage of towers, poles and lines, damage and inundation to other structures. *Site exclusion:* Yes – where possible all equipment should be located away from known flow paths. *Design:* Locating services underground. Construction of embankments around critical components. *Contingency planning:* –	*Vulnerability:* Breakage of towers, poles and lines, damage to other structures, sedimentation in HEP storage reservoirs, abrasion of HEP turbines. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow paths. *Design:* Locating services underground. Construction of embankments around critical components. Use of hardened materials to limit abrasion. *Contingency planning:* Use of early warning systems, rain gauges and flow sensors. Clean up operations and methods.

Infrastructure sector	Hazard			
	Tephra fall	PDC	Lava flow	Lahar
Water supply network	*Vulnerability:* Increased turbidity, decreased water quality, increased water demand, clogging of filters, abrasion of moving parts in motors and pumps, corrosion of metals. *Site exclusion:* No *Design:* Strengthen structures to minimise tephra load damage. Cover open filter beds, clarifiers and pumps. Consider the use of groundwater sources in increase resilience. *Contingency planning:* Tephra clean-up operations using dry methods (brooms, shovels). Anticipate increased water demand and possible contamination. Increase maintenance frequency. Close water intakes until turbidity decreases.	*Vulnerability:* Lateral loading damage to tanks, well heads and pipes. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow paths. *Design:* Strengthen all structures at treatment facility. Strengthen pipes crossing flow paths or locate them deep underground. *Contingency planning:* Clean-up operations and methods. Anticipate possible water contamination.	*Vulnerability:* Burial of underground access points, rupturing of pipes. *Site exclusion:* Yes – where possible all equipment should be located away from known flow paths. *Design:* Construction of embankments around critical components. *Contingency planning:* –	*Vulnerability:* Lateral loading damage to tanks, well heads and pipes, erosive damage to underground pipes, abrasion damage to river intake structures. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow paths. *Design:* Use of abrasion resistant materials for intake structures in rivers. *Contingency planning:* Clean-up operations and methods. Anticipate possible water contamination. Close water intakes until turbidity decreases. Use of early warning systems.

Infrastructure sector	Hazard			
	Tephra fall	PDC	Lava flow	Lahar
Wastewater network	*Vulnerability:* Abrasion damage to components with moving parts, blockage of filters and screens, ingress into pipe network and treatment facility. *Site exclusion:* No *Design:* Strengthen structures to minimise tephra load damage. Cover exposed equipment, tanks and pumps. Limit tephra ingress by utilising separate stormwater system. *Contingency planning:* Tephra clean-up operations and methods. Increase maintenance frequency. Consider bypassing pumping stations and treatment facilities to protect against further equipment damage.	*Vulnerability:* Lateral loading damage to structures and equipment, ingress into pipe network. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow paths. *Design:* Strengthen all structures at treatment facility. Strengthen pipes crossing flow paths or locate them deep underground. *Contingency planning:* Clean-up operations and methods.	*Vulnerability:* Lateral loading damage to structures and equipment. Burial of underground access points. *Site exclusion:* Yes – where possible all equipment should be located away from known flow paths. *Design:* Construction of embankments around critical components. *Contingency planning: –*	*Vulnerability:* Lateral loading damage to structures and equipment, ingress into pipe network. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow paths. *Design:* Construction of bunds around oxidation ponds to prevent lahar ingress. *Contingency planning:* Clean-up operations and methods. Use of early warning systems.

Infrastructure sector	Hazard			
	Tephra fall	PDC	Lava flow	Lahar
Transportation networks	*Vulnerability:* Reduced visibility and traction, covering of road and runway markings, abrasion and corrosion damage to vehicles, jamming of rail switches, and disruption to airspace. *Site exclusion:* No *Design:* Strengthen buildings (airports, train stations) and increase roof pitch to minimise tephra load damage. *Contingency planning:* Tephra clean-up operations and methods. Road, rail and airport closure protocols. Established tephra avoidance guidelines for aircraft.	*Vulnerability:* Burial of roads, rail networks and airport runways, increased sedimentation into harbours, erosive damage and destruction of bridges, extensive damage to vehicles. *Site exclusion:* Yes – where possible all routes should be located away from valleys and known flow paths. *Design:* Raise bridge decks over valleys and strengthen piers and abutments. *Contingency planning:* Identify alternate routes if primary routes are damaged. Anticipate the need for temporary bridges. Clean up operations and methods.	*Vulnerability:* Burial of roads, rail networks and airport runways. *Site exclusion:* Yes – where possible all routes should be located away from known flow paths. *Design:* Construction of embankments around critical parts of the network. *Contingency planning:* –	*Vulnerability:* Burial of roads, rail networks and airport runways, increased sedimentation into harbours, erosive damage and destruction of bridges, extensive damage to vehicles. *Site exclusion:* Yes – where possible all routes should be located away from valleys and known flow paths. *Design:* Automated barriers to close road and rail routes when lahars occur. Raise bridge decks over valleys and strengthen piers and abutments. *Contingency planning:* Use of early warning systems. Identify alternate routes if primary routes are damaged. Anticipate the need for temporary bridges.

Infrastructure sector	Hazard			
	Tephra fall	PDC	Lava flow	Lahar
Communications	*Vulnerability:* Signal interference and attenuation, corrosion of metal surfaces. *Site exclusion:* No *Design:* Strengthen structures or use tephra shedding designs to minimise tephra loading. Sealing of equipment to prevent tephra ingress. *Contingency planning:* Tephra clean-up operations and methods. Use of different redundant and backup communication systems. Increase maintenance frequency.	*Vulnerability:* Signal interference and attenuation, damage of towers, poles and masts, burial of equipment. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow paths. *Design:* Locate services underground or inside strengthened buildings. Strengthen all equipment, especially those crossing flow paths. *Contingency planning:* Clean-up operations. Increase maintenance frequency.	*Vulnerability:* Damage of towers, poles and masts, burial of equipment. *Site exclusion:* Yes – where possible all equipment should be located away from known flow paths. *Design:* Construction of embankments around critical parts of the network. Locate equipment inside strengthened buildings. *Contingency planning:* –	*Vulnerability:* Damage of towers, poles and masts, burial of equipment. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow paths. *Design:* Locate services underground or inside strengthened buildings. Strengthen all equipment, especially those crossing flow paths. *Contingency planning:* Clean-up operations. Increase maintenance frequency. Use of early warning systems.
Critical components	*Vulnerability:* Clogging of air filters, overheating, short circuits, abrasion of moving parts, corrosion of metal surfaces. *Site exclusion:* No	*Vulnerability:* Destruction and transportation of equipment. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow	*Vulnerability:* Destruction and burial of equipment. *Site exclusion:* Yes – where possible all equipment should be located away from known flow paths.	*Vulnerability:* Destruction and transportation of equipment. *Site exclusion:* Yes – where possible all equipment should be located away from valleys and known flow

Infrastructure sector	Hazard			
	Tephra fall	PDC	Lava flow	Lahar
	Design: Seal equipment and locate equipment inside sealed buildings to prevent tephra ingress. Install air filters designed for fine particles. Install hoods over HVAC air intakes. *Contingency planning:* Tephra clean-up operations and methods. Increase maintenance frequency.	paths. *Design:* Relocation of equipment into strengthened buildings. *Contingency planning:* Clean-up operations and methods. Increase maintenance frequency.	*Design:* Relocation of equipment into strengthened buildings. *Contingency planning:* –	paths. *Design:* Relocation of equipment into strengthened buildings. *Contingency planning:* Use of early warning systems. Clean up operations and methods. Increase maintenance frequency.
Buildings	*Vulnerability:* Blocked and/or damaged gutters, tephra ingress, corrosion of metal surfaces, structural damage to roof. *Site exclusion:* No *Design:* Strengthen roofs, increasing roof pitch to reduce static load. *Contingency planning:* Sealing of building to prevent tephra ingress. Removing tephra from roof to prevent	*Vulnerability:* Damage to windows and doors, structural damage to whole building, inundation and burial, ignition of fires. *Site exclusion:* Yes – where possible all buildings should be located away from valleys and known flow paths. *Design:* Strengthen walls and avoid having them perpendicular to flow path to reduce dynamic load. Use of	*Vulnerability:* Structural damage to whole building, burial, ignition of fires. *Site exclusion:* Yes – where possible all buildings should be located away from known flow paths. *Design:* Strengthen building walls. Use of non-flammable materials. *Contingency planning:* –	*Vulnerability:* Inundation and burial, structural damage to walls, float building off foundations. *Site exclusion:* Yes – where possible all buildings should be located away from valleys and known flow paths. *Design:* Strengthen walls and avoid having them perpendicular to flow path to reduce dynamic load. Fix

Infrastructure sector	Hazard			
	Tephra fall	PDC	Lava flow	Lahar
	collapse.	shutters on openings to prevent ingress. *Contingency planning:* Evacuation planning and implementation.		buildings to foundations. *Contingency planning:* Use of early warning systems. Evacuation planning and implementation.

[a] A 'yes' for site exclusion indicates that infrastructure development should be avoided at a particular site as damage from a hazard cannot be mitigated.
[b] Design considerations include altering the design of components and infrastructure sectors to lower their vulnerability to disruption and damage from volcanic hazards (e.g., strengthen building roof) and the design of site protection measures for flow hazards (e.g., construction of diversion barriers).
[c] Contingency planning involves making decisions and plans in advance about the management and response to volcanic eruptions to minimise impact severity and decrease recovery time (e.g., evacuation plans, clean-up plans and availability of resources).

2.4.1 Electrical supply networks

Electricity is essential for a functioning modern society and the continued operation of other critical infrastructure. Electrical equipment and apparatus used in power generation, transmission and distribution is typically located above ground, comprising of a series of nodes (power stations, substations) connected by extensive corridors (transmission and distribution lines) which can stretch thousands of kilometres (Figure 2.3A). The ubiquitous scope of the electrical supply network increases its level of exposure making the network particularly vulnerable to volcanic hazards (Wardman et al., 2012c). Volcanic hazards affect the electric supply network in a number of ways (Figure 2.4), the most common being temporary outages caused by insulator flashover as a result of tephra accumulation (Wardman et al., 2012c). Many of the impacts discussed below can occur at any location within the network as similar equipment is located throughout the network (Figure 2.3A). See Wardman et al. (2012c) for a review of tephra fall impacts and mitigation strategies for the electrical supply network.

2.4.1.1 Insulator flashover

The most common tephra fall impact on the electrical supply network is insulator flashover (Wardman et al., 2012c). A flashover is an unintended electrical discharge (short circuit) around the insulator and typically leads to a line fault. Dry tephra has high resistivity but in the presence of moisture resistivity becomes very low (Wardman et al., 2012b). So when tephra is deposited on insulators, in the presence of moisture, a flashover may result. It may only take one insulator to suffer flashover for an entire line of potentially hundreds of kilometres to be disrupted. Tephra, in this case, can result from direct falls, PDCs or from wind remobilisation of unconsolidated tephra deposits. Flashover has been observed worldwide after volcanic eruptions where tephra accumulations exceed ~3 mm (Figure 2.4). However tephra moisture content is the critical factor controlling flashover occurrence, as dry tephra has very low electrical conductivity (Wardman et al., 2012b). Insulator and system design also influence flashover susceptibility. Wardman et al. (2012c) found that tephra accumulations on the underside of insulators are equally important as accumulations on the topside in assessing vulnerability. Electrical supply providers can minimise tephra induced flashover by increasing insulation, using anti-pollution designs and cleaning strategies (Wardman et al., 2012c).

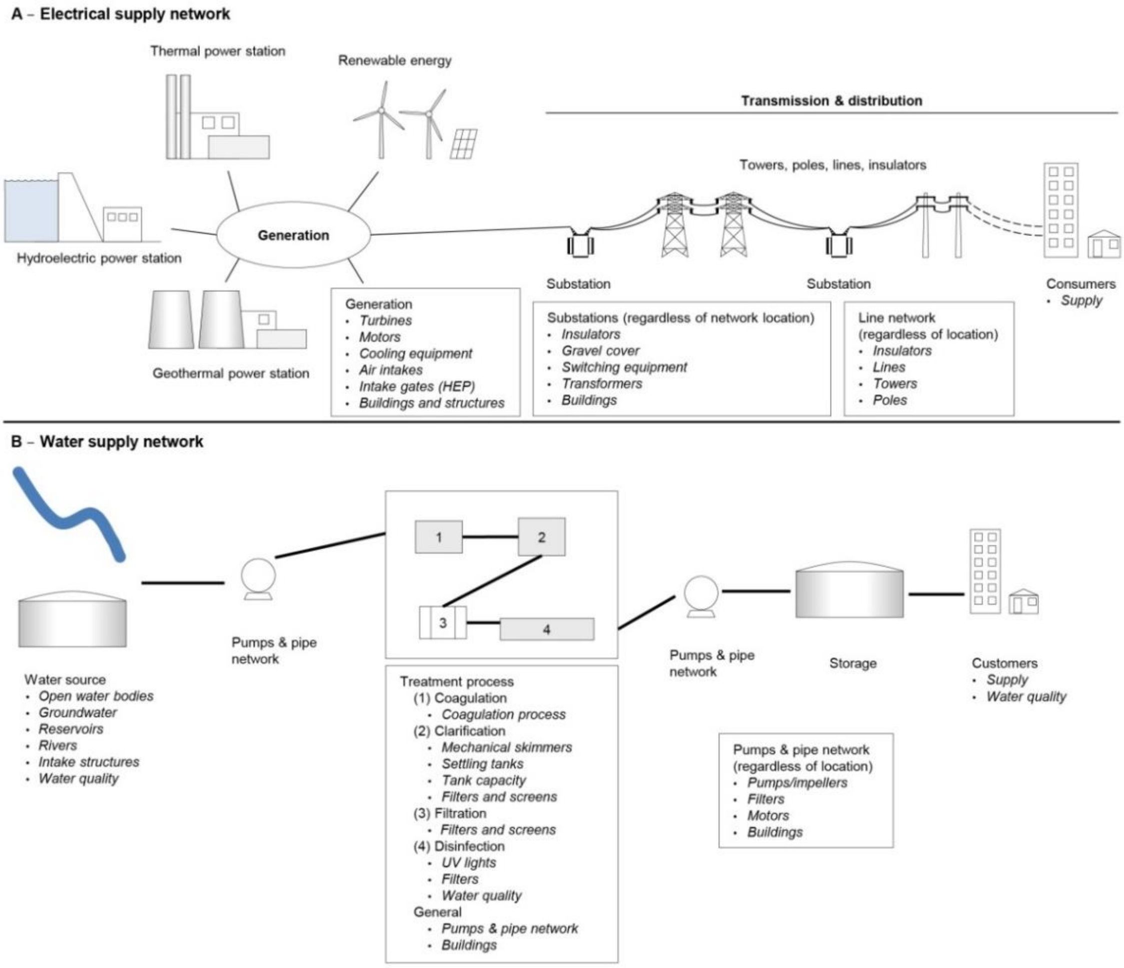


Figure 2.3: Schematic of (A) an electrical supply network showing generation at different power stations and then transmission and distribution to consumers (modified from Wardman et al., 2012c) and (B) a water supply network from water source, water treatment through to distribution to consumers. Components vulnerable to volcanic hazards are indicated in italics.

Tolerance to flashover faults and continued operation of electrical networks has been documented in some cases (Figure 2.4), although Wardman et al. (2012c) suggests that may be under-reported as it is more common to document failures. Tolerance is observed over a wide range of tephra fall thicknesses ranging from 2 to 300 mm. Differences in tolerance values are due to different component designs, tephra properties and environmental conditions, as these parameters influence how tephra affects insulators.

2.4.1.2 Damage to electrical lines

Volcanic flows have snapped poles and damaged electrical lines, resulting in supply disruption, during volcanic eruptions of: Heimaey, Iceland in 1973 (lava flows: Morgan, 2000); Mauna Loa, Hawaii in 1984 (lava flows: Associated Press, 1984; Hawaiian Volcano Observatory, 1998a); Nyiragongo, Democratic Republic of the Congo (DRC) in 2002 (lava flows: Baxter and Ancia, 2002); Chaitén, Chile in 2008 (lahars: Wilson et al., 2009); and Merapi in 2006 (PDCs: Wilson et al., 2007). Figure 2.5 shows that these impacts tend to occur at low hazard intensities although the scarce evidence suggests any presence of volcanic flows is likely to cause disruption to electrical infrastructure. Tephra accumulations on lines may cause them to break as occurred in the 2008 eruption of Chaitén, although here snow added to the load on the lines (T.M. Wilson et al., 2012). Flow deposits, especially solidified lava flows, will restrict access to buried services (e.g., underground cables) limiting future serviceability.

2.4.1.3 Damage at generation sites

Hydroelectric power (HEP) turbines at generation sites are particularly vulnerable to abrasion after tephra material (either from direct fall or PDCs and lahars) is deposited into storage reservoirs. Tephra suspended in reservoirs may pass through turbines causing abrasion to them and other auxiliary components over time (Figure 2.6A). Abrasion reduces the performance and life span of turbines leading to turbine replacement (e.g., Meredith, 2007). For example, four turbines at the Agoyan HEP station, Ecuador have been replaced in the last 21 years as a result of abrasion damage from ongoing tephra fall from Volcán Tungurahua being deposited in the Pastaza catchment (Sword-Daniels et al., 2011). Tephra properties (e.g., particle hardness and morphology) and exposure time are the primary controls on abrasion occurrence with longer exposure times leading to increased abrasion severity. Although turbine design, materials, protective coatings and maintenance will also influence abrasion damage. Wind turbines and blades are also at risk of abrasion by tephra particles and may result in damage and reduced performance similar to that caused by sand particles (e.g., Khalfallah and Koliub, 2007; Dalili et al., 2009).

The only known example of a geothermal power generation site being impacted by tephra fall is the Amatitlán plant located 3 km north of Volcán Pacaya, Guatemala. During the 2010 eruption of Pacaya, the plant received 200 mm of coarse tephra and bombs up to 250 mm in diameter. The upward facing uncovered steam condenser fans suffered abrasion damage and denting from falling blocks, rendering them non-operational (Wardman et al., 2012a). Minor denting of intake and outlet pipe cladding also occurred. The plant was shut down for three weeks while cleaning was undertaken (Wardman et al., 2012a).

Lahars have been documented impacting river water intake systems used for generation site cooling. After the 1980 Mt. St. Helens eruption, lahars filled the Columbia River with sediment, the same river where the now decommissioned Trojan Nuclear Power Plant had a water intake system. Fortunately the water intake was located in an area with less sedimentation and the plant was off-line at the time of the eruption for fuel replacement (Schuster, 1981).

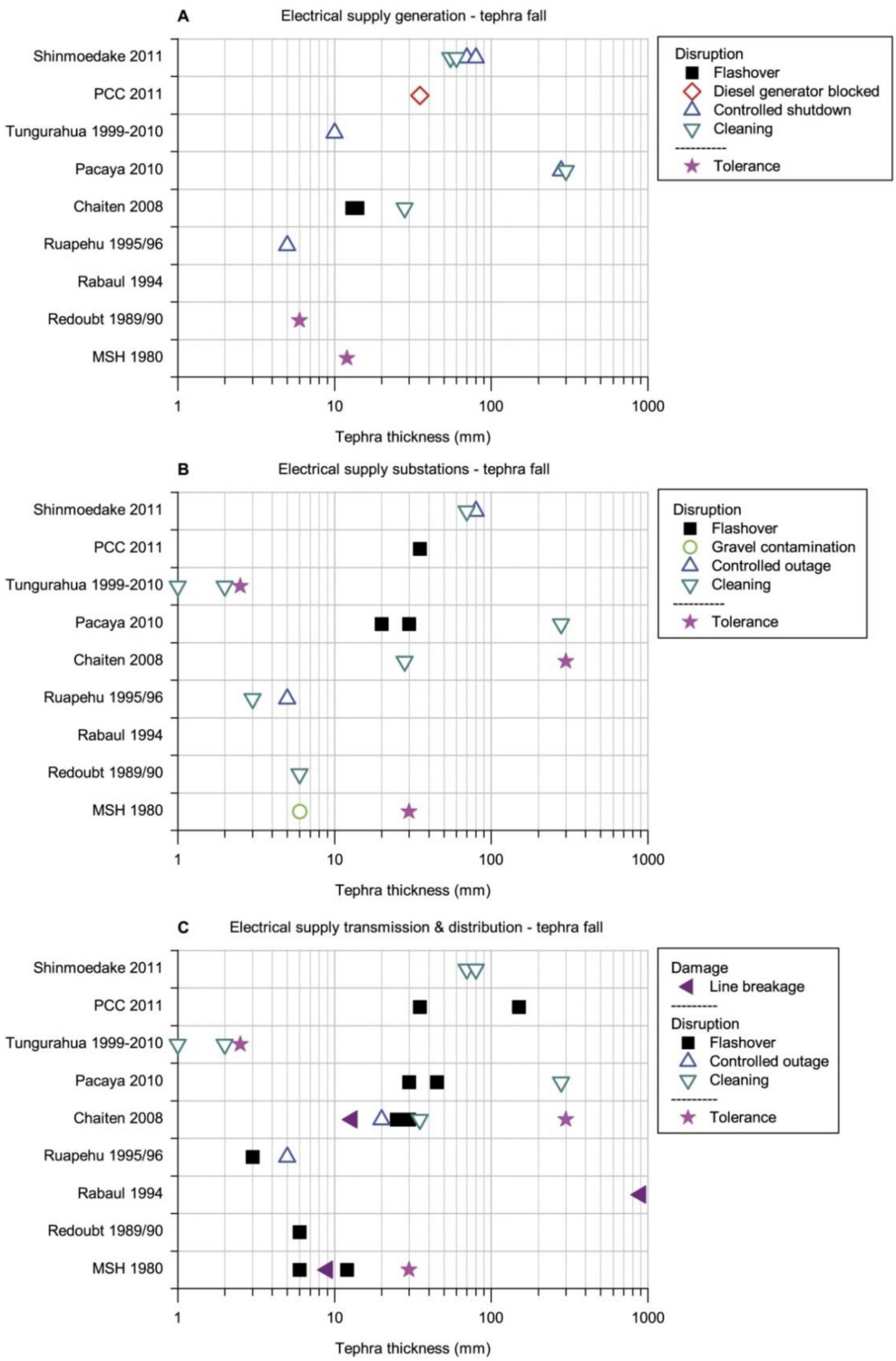


Figure 2.4: Summary of documented tephra fall impacts and disruption to the electrical network as a function of tephra thickness for (A) generation, (B) substations and (C) transmission and distribution (modified from Wardman et al., 2012c). Note: only data where tephra thickness is known or derived are plotted.

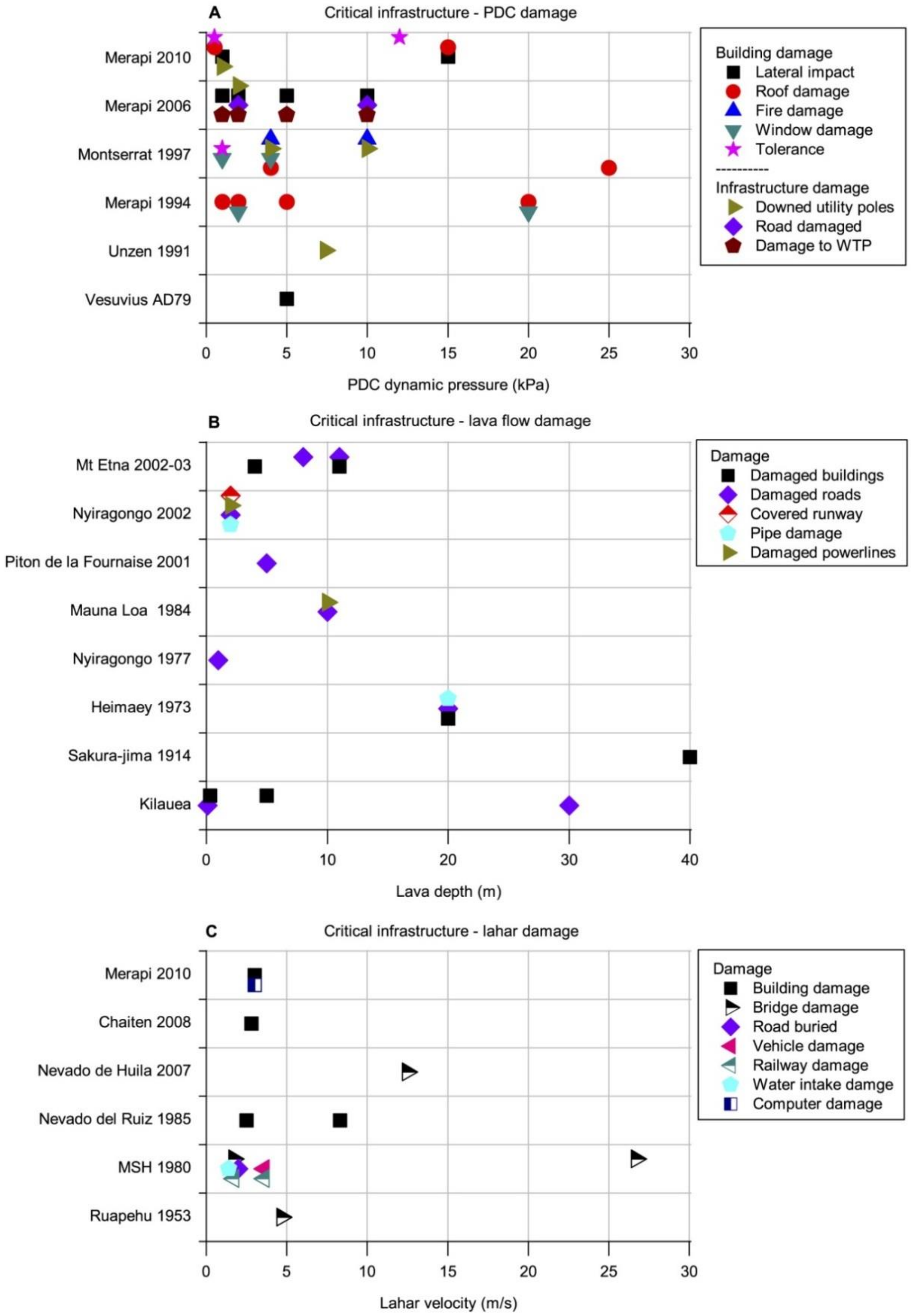


Figure 2.5: Summary of documented critical infrastructure impacts from (A) PDCs, (B) lava flows and (C) lahars as a function of hazard intensity. Note: only data where tephra thickness is known or derived are plotted.

New renewable energy technologies such as photovoltaic (PV) panels may be impacted by volcanic hazards as they are open to the atmosphere; however there is limited empirical observation of this occurring. One instance occurred during the 2011 eruption of Shinmoedake, Japan, when tephra accumulated (<2 mm) on PV panels at the University of Miyazaki, 50 km east of the vent. PV panel performance was reduced by ~60% (Ota et al., 2012) but recovered after rainfall removed the tephra a few days later.

2.4.1.4 Clean-up disruption

Deposition of unconsolidated tephra deposits either from direct falls or flows (PDCs and lahars) at electrical supply sites may require removal to restore function. Tephra clean-up operations have been used by electrical supply operators worldwide to minimise ongoing flashover faults and prevent future tephra induced impacts (e.g., corrosion, abrasion) to their components and network (Figure 2.4). Documented thicknesses of when cleaning occurs is varied; ranging from 1 mm after eruptions at Tungurahua (1999–2010) to >100 mm after the eruption of Pacaya in 2010 (Figure 2.4). This range in thickness can be attributed to infrastructure design, tephra properties and the operational practices of the particular electrical supply providers. In some instances cleaning can be undertaken while components are energised, reducing the need to shut down and limiting disruption (Wardman et al., 2012c), however, controlled shutdowns may be necessary in order to protect equipment and personnel (Sword-Daniels et al., 2011) (Figure 2.4). Controlled shutdowns will cause supply disruptions unless there are redundant networks capable of supplying electricity while cleaning is undertaken.

Figure 2.6: (A) Abrasion damage to a turbine removed from the Agoyan hydroelectric power station, Ecuador as a result of exposure to tephra laden water derived from the 1999–2010 eruptions of Volcán Tungurahua (Photo: Johnny Wardman). (B) Houses covered with a thin layer of tephra after the eruption of Mt. Kelud on February 14, 2014 (Photo: Dwi Oblo). (C) personnel cleaning tephra from the Bariloche, Argentina water treatment plant after the June 4, 2011 eruption of PCCVC (Photo: Carol Stewart). (D) laboratory experiments to determine settling rate of tephra in water. Each beaker contains a different tephra and shows the turbidity after one hour of settling (Photo: J White).

2.4.2 Water supply networks

Water supply networks are comprised of water source, water treatment and storage sites as well as a vast distribution network of mostly underground pipes. There are numerous vulnerable components throughout the network that can be impacted by volcanic hazards (Figure 2.3B). The majority of documented impacts to water supply are due to tephra falls causing disruption and minor damage (Figure 2.7A). The less frequent volcanic flow impacts tend to cause physical damage (Figure 2.5). Stewart et al. (2009b) groups impacts to water networks into three categories: (1) direct physical damage; (2) changes in water quality; and (3) water demand issues which are very much controlled by system design. We follow this structure here.

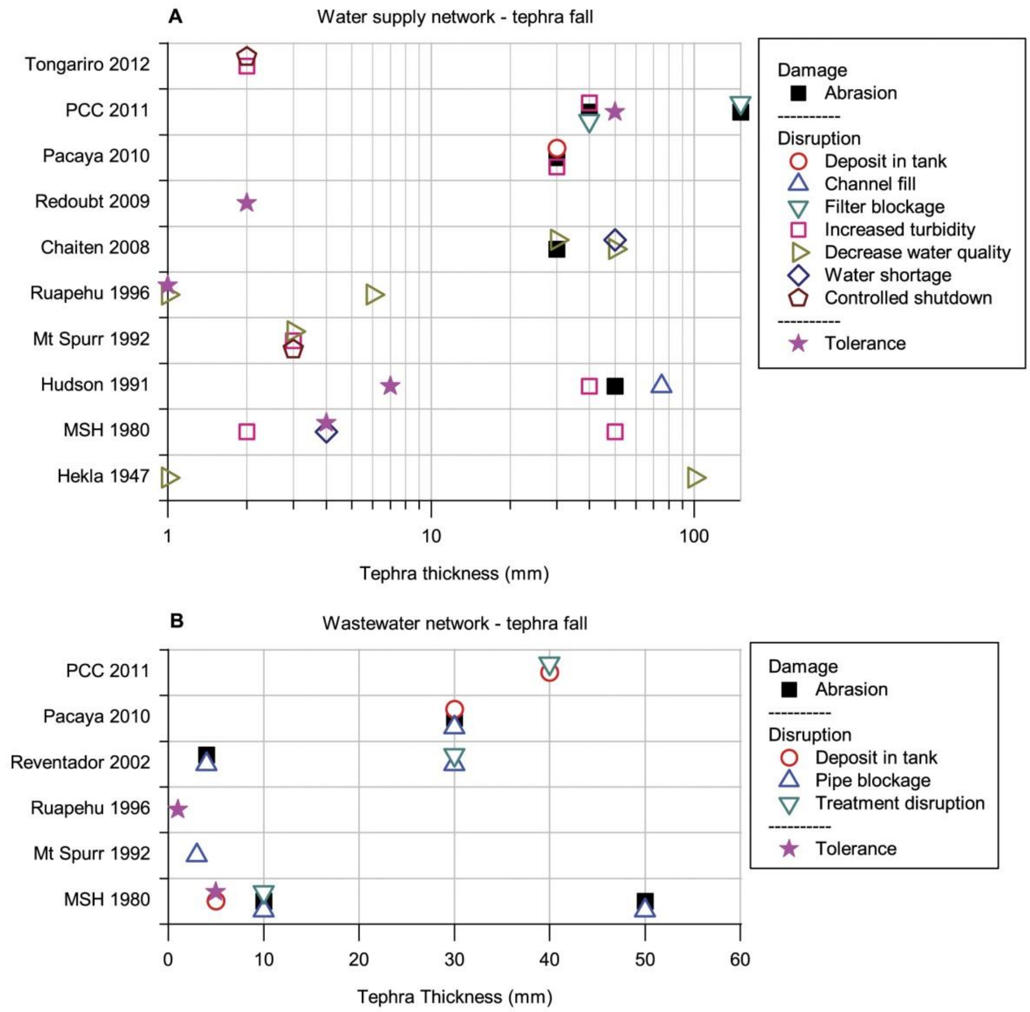


Figure 2.7: (A) Summary of documented tephra fall impacts and disruption to (A) the water supply network and (B) the wastewater network as a function of tephra thickness. Note: only data where tephra thickness is known or derived are plotted.

2.4.2.1 Physical damage

Physical damage to water supply networks tends to be caused by volcanic flows, heavy tephra falls and prolonged exposure to tephra. Volcanic flows have caused complete destruction of water supply infrastructure as a result of increased lateral loading

(Figure 2.5). Groundwater well heads, springs, reservoirs and pipes were damaged around Montserrat by PDCs (Howe, 2003) and lahars (CDERA, 2006) during the 1995 eruption of Soufrière Hills volcano. Water pipes have been damaged and buried by lahars around Mayon volcano, Philippines (Nasol, 2001; Smithsonian Institution, 2002) and by lava flows in Goma, DRC after the 2002 eruption of Nyiragongo (Smithsonian Institution, 2001; Baxter and Ancia, 2002). These examples show that water supply infrastructure located above ground in or near flow paths (i.e., river valleys) are vulnerable to damage from volcanic flows at low hazard intensities (Figure 2.5).

Direct tephra falls or exposure to tephra-water slurries (such as those in pipes) can cause minor physical damage in the form of abrasion of moving parts (e.g., pumps, motors) and corrosion of metals. Damage of this nature is documented after numerous eruptions (Stewart et al., 2006; T.M. Wilson et al., 2012) and is attributed to tephra thicknesses exceeding 30 mm (Figure 2.7A), however duration of exposure is the primary control on this type of damage, which is difficult to establish in these cases. Tephra-induced damage reduces pumping efficiency which leads to reduction in production and distribution capacity and increased maintenance and/or repair of pumps and pipes.

2.4.2.2 Disruption to water treatment

Disruption and increased maintenance from tephra falls is more common than physical damage (T.M. Wilson et al., 2012). Treatment disruption occurs when there is partial to complete blockage of water intakes, filters and pipes, as these have to be cleaned before normal operation can resume (Figure 2.6C). These impacts can occur at tephra thicknesses >1 mm (Figure 2.7A). This can be illustrated from a case study from the 2011 eruption of Puyehue-Cordón Caulle volcanic complex (PCCVC), Chile. During this eruption the town of Bariloche, 100 km from the vent, received 30–45 mm of tephra and the town of Jacobacci, 240 km from the vent, received 50 mm of tephra (Wilson et al., 2013). The Bariloche plant was designed for low levels of suspended solids and raw water passed directly through the sand filters. During the eruption, tephra laden water blocked filter pore spaces requiring additional daily cleaning to return filter functionality and water treatment capacity (Wilson et al., 2013). In contrast, in Jacobacci water supplies were resilient to disruption as all pump houses were enclosed and water is sourced from groundwater wells (Wilson et al., 2013). This example illustrates that system design will affect impact occurrence and severity (Stewart et al., 2009b).

2.4.2.3 Water quality impacts

Raw and treated water within water supply networks can also be impacted by volcanic hazards and requires consideration in vulnerability assessments. We refer the reader to Stewart et al. (2006; 2009a, b) and T.M. Wilson et al. (2012) for in-depth reviews.

Water quality impacts occur when tephra, from either tephra falls or PDCs, enters water source areas or treatment facilities (Figure 2.3B). Tephra will cause an increase in turbidity (cloudiness of water caused by suspended particles) at tephra thicknesses >2 mm (Figure 2.6 and 2.7A) (Stewart et al., 2006). Chemical contamination of water occurs as soluble surface coatings on fresh tephra particles dissolve readily upon contact with water, releasing a range of ions (Witham et al., 2005; Delmelle et al., 2007). Increased ion concentration may breach drinking water standards, however this is usually only for short time periods (Stewart et al., 2009a). Chemical contamination of water supplies from tephra fall is difficult to predict prior to an eruption due to variability in soluble salt and water chemistry, however can occur at tephra thicknesses >1 mm (Figure 2.7). Turbidity and chemical contamination is commonly controlled though management practices (Stewart et al., 2009b), however if turbidity becomes too high to treat effectively, the treatment plant may have to shut down. This occurred at the Ship Creek treatment facility in Anchorage which received 3 mm of tephra was shut down for 30 hours as a precaution following the 1992 eruption of Mt. Spurr, Alaska (T.M. Wilson et al., 2012).

2.4.2.4 Water shortages

After tephra falls, clean-up is commonly undertaken by washing away unconsolidated deposits placing large demands on water resources (T.M. Wilson et al., 2012). In 1992 Anchorage, Alaska was covered with 3 mm of tephra from the eruption of Mt Spurr. After residents began cleaning tephra deposits, there were severe water shortages and loss of pressure in some parts of the city (Stewart et al., 2009b). In contrast, successful management of water supply occurred in Esquel, Argentina during the eruption of Chaitén volcano in 2008. During residential clean-up supply exhaustion was avoided as authorities advised residents to use alternative ‘dry’ clean-up methods such as use of brooms and shovels (Stewart et al., 2009b).

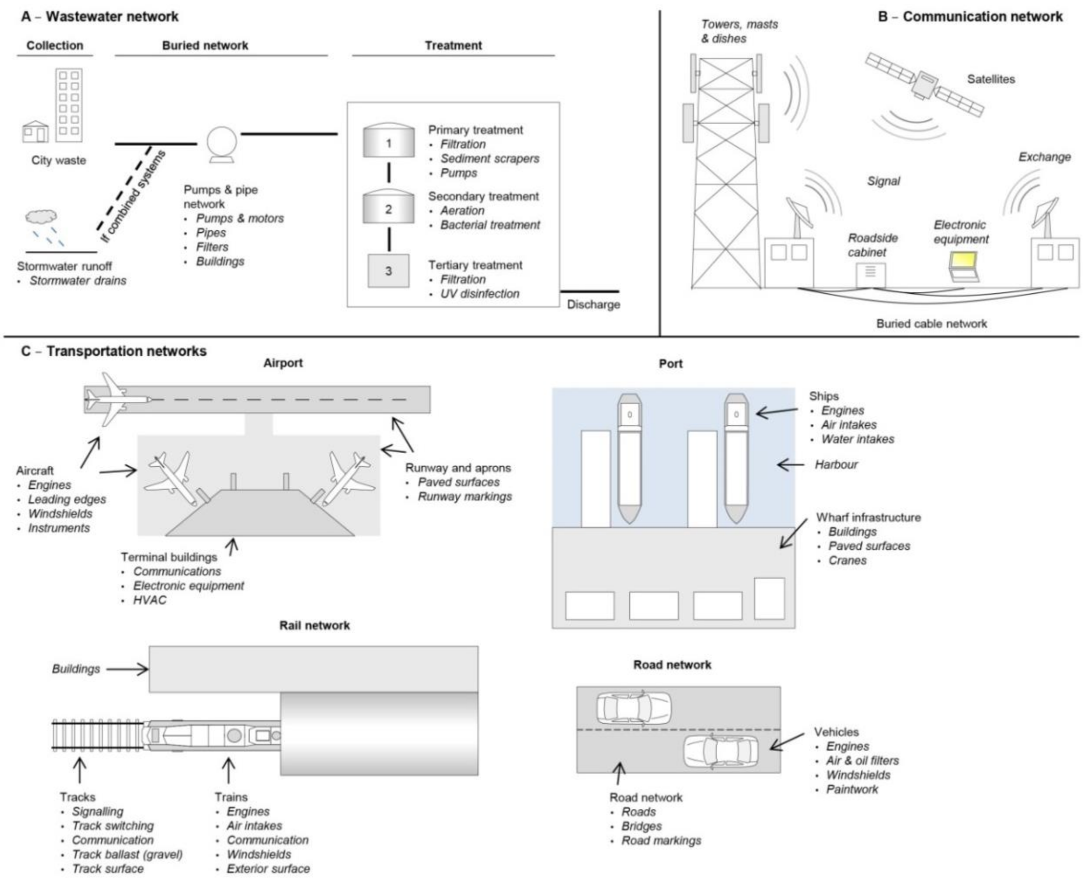


Figure 2.8: Schematic of (A) wastewater and stormwater collection and treatment network, (B) typical components used within communication networks and (C) air, rail, sea and road transportation networks and vehicles. Components vulnerable to volcanic hazards are indicated in italics.

2.4.3 Wastewater treatment networks

Wastewater networks comprise an underground network of pipes and pumps and above ground treatment facilities (Figure 2.8A). Wastewater networks may be combined with stormwater systems or the two may be completely separate. Combined wastewater and stormwater systems are more vulnerable to impacts than separate systems because unconsolidated material can easily enter the network through stormwater drains (Barnard, 2009).

2.4.3.1 Physical damage

There is limited documented evidence of volcanic flows directly impacting wastewater treatment facilities, except for the case of Plymouth, Monserrat in which the entire town was destroyed by pyroclastic flows from Soufrière Hills volcano in 1997 (Rozdilsky, 2001). Abrasion damage to pumps, pipes, sediment scrapers, filtration components and debris screens may occur as tephra laden slurries pass through these components (Blong, 1984; Johnston, 1997; Barnard, 2009) again occurring over extended periods of time. Eruptions from Mt. St. Helens (1980), El Reventador, Ecuador (2002) and Pacaya (2010) show abrasion damage occurring over a range of tephra thicknesses from 4–50 mm (Figure 2.7B).

2.4.3.2 Treatment disruption

Wastewater treatment can be disrupted if tephra is deposited directly onto treatment facilities as the capacities of open ponds, reactors and clarifiers will be reduced (Figure 2.7B) (T.M. Wilson et al., 2012). For example, disruption occurred during the 2010 eruption of Pacaya volcano when a combined sludge and sedimentation tank in Guatemala City filled with 4–5 m of tephra and had to be cleaned before continued operation (T.M. Wilson et al., 2012). Tephra can form large hardened and unpumpable masses within the pipe network which require manual removal (T.M. Wilson et al., 2012). Figure 2.7B suggests pipe blockage occurs with tephra thicknesses >3 mm however accumulations larger than this may occur in pipes. Blockages are likely to occur at distinct points and not throughout the entire network.

If treatment disruption and/or damage become excessive, wastewater might have to bypass the system and be discharged in to the environment as untreated waste. This decision was made at the Yakima waste treatment facility, USA after it received 10 mm of tephra from the 1980 Mt. St. Helens eruption (Blong, 1984). Tephra caused damage to most of the treatment facility including the biofilters and a decision was made four days after the eruption to bypass treatment and discharge waste, after chlorination, into the Yakima River (Blong, 1984). The decision was made because continued operation of the plant would have caused greater damage and more periods of discharge would have occurred in the future.

2.4.4 Transportation networks

Transportation networks can be vast and cover large expanses of the landscape, increasing their exposure to volcanic hazards similar to electrical networks (Figure 2.8C). Volcanic hazards have been documented adversely affecting all transportation systems (e.g., road networks, vehicles, rail tracks, trains, ports, ships, airports; Figure 2.5 and 2.9A). Additionally, a number of cascading impacts may occur, not discussed here, affecting other sectors which rely on transportation, as well as possible evacuation and emergency response during a volcanic crisis.

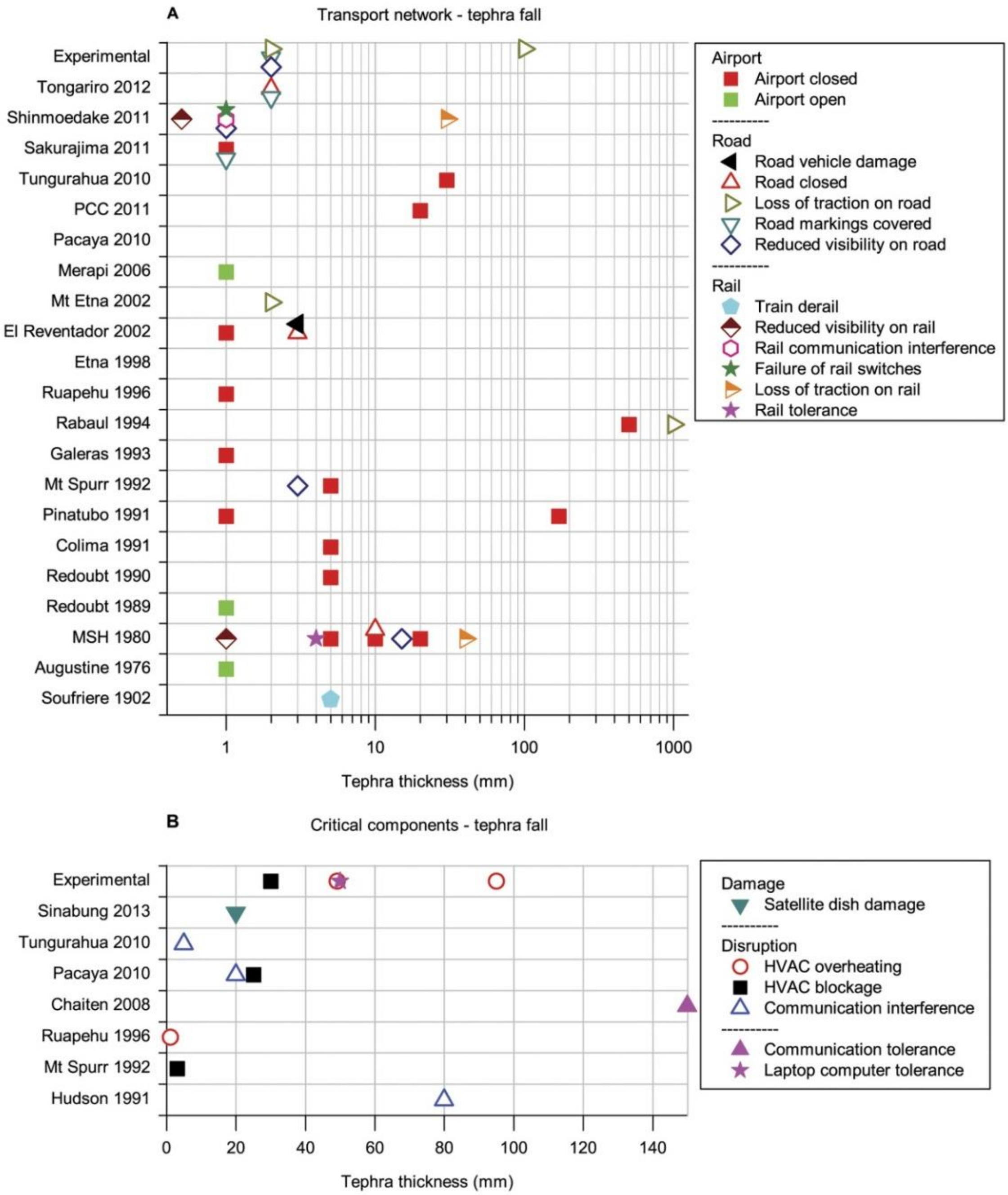


Figure 2.9: Summary of documented tephra fall impacts and disruption to (A) the transportation network and (B) critical components and communication equipment as a function of tephra thickness. Note: only data where tephra thickness is known or derived are plotted.

2.4.4.1 Road networks and vehicles

Physical damage

Volcanic flows can cause physical damage to road networks (Figure 2.5). Perhaps the best known example of this was after the 1980 eruption of Mt. St. Helens where lahars and PDCs caused extensive damage or destruction to 300 km of road and 48 bridges in the valleys draining the volcano (Blong, 1984). Bridges are particularly vulnerable as they generally cross flow paths and can be damaged by scouring around abutments and piers and lateral loading (Nairn, 2002). Roadways located on flow channel banks are vulnerable to undercutting by lahars. For example, three months after the 2010 eruption of Merapi volcano, Indonesia, a lahar eroded a 60 m section of a major highway causing its closure (Smithsonian Institution, 2011).

Lava flows, regardless of depth, cause irreparable damage to roads around the world by simply crossing them (Figure 2.5B). Since the early 1900s, numerous roads in Hawaii have been covered by lava from eruptions of Mauna Loa and Kilauea (Blong, 1984; Hawaiian Volcano Observatory, 1998b, 2000). Thin (<1 m) flows buried a main road in Goma during the 1977 Nyiragongo eruption, DRC (Blong, 1984) and again during the 2002 eruption (Baxter et al., 2003). Sections of roads along the western and southern flanks of Mt. Etna, Italy have been buried numerous times by lava flows (Smithsonian Institution, 1999; Andronico et al., 2005). These examples indicate that lava flows conform to a binary impact model based on the presence or absence of lava.

PDCs can move, overturned, burn and/or impact vehicles located in flow paths. For example, vehicles within 15 km of Mt. St. Helens were totally destroyed by the 1980 eruption (Blong, 1984). During the September 1991 Unzen, Japan eruption, a vehicle sustained extensive panel damage, was burnt and transported 120 m by PDCs (Fujii and Nakada, 1999). Lahars are also likely to completely damage vehicles as they are carried downstream whilst being impacted by debris (Blong, 1984); however reports are limited. Tephra particles can damage vehicles by abrading moving parts and blocking air and oil filters (T.M. Wilson et al., 2012). Windshields and paintwork are highly susceptible to abrasion from tephra, which can be made worse by attempting to clean these surfaces. Despite possible damage, resilience has also been documented. For example, in Yakima, USA, after the 1980 Mt. St. Helens eruption, 30 police cars which were used during tephra falls suffered no long term damage, other than increased oil change frequency (Blong, 1984).

Disruption

Decreased road drivability in the form of traction loss, covered road markings and poor visibility (Figure 2.10) can result from tephra fall or remobilised unconsolidated tephra deposits (Nairn, 2002; Leonard et al., 2005; T.M. Wilson et al., 2012). These impacts start to occur at thin (~2–3 mm) tephra thicknesses (Figure 2.9A). Disruption may increase as authorities close roads, limit the number of circulating vehicles or lower the speed limit to decrease the likelihood of traffic accidents and limit tephra remobilisation. Clean-up operation following tephra fall will restore road drivability although it may be possible to drive on thick tephra deposits as they become compacted over time.

Figure 2.10: A sequence of photos, from left to right, showing the remobilisation of tephra and decrease in visibility from a passing car as the car travels towards the observer (Photos: G Leonard).

2.4.4.2 Rail network and trains

Physical damage

Rail bridges are vulnerable to lahar damage as they are likely to cross lahar paths. In 1953, a lahar travelled down the Whangaehu River on the slopes of Mt. Ruapehu, New Zealand and collapsed part of the Tangiwai rail bridge minutes before the a passenger train arrived (O'Shea, 1954; Scott, 2013). The train derailed and plunged into the river; 151 people were killed. Valentine (1998) studied damage from nuclear weapon blasts and inferred PDC damage to trains and rail tracks will occur at dynamic pressures >10 kPa. Lava flows have blocked, covered and damaged railway lines numerous times in the 1900s around Mt. Etna and Mt. Vesuvius, Italy rendering them unusable (Blong, 1984). It is likely that railways lines covered by lava flows of any depth will result in complete localised damage.

Disruption

Disruption to the rail network is most likely from tephra fall. The best documented example of tephra fall impacting rail networks is the 2011 Shinmoedake eruption in Japan. Here 168 km of track and 48 stations were impacted by tephra, causing delays and cancellations (Smithsonian Institution, 2010; Magill et al., 2013). The main issues were the mechanical failure of track switches and loss of electrical contact between the track and train (Figure 2.9A), which in this rail network is how communications are sent to the train operator. Problems did not begin at a particular critical threshold, and therefore a zero tolerance policy was adopted with services cancelled until tephra was removed (Magill et al., 2013). Track ballast (crushed gravel used to support tracks) was infiltrated by tephra, reducing its cushioning properties and required frequent replacement. Tephra also infiltrated train carriages, requiring additional cleaning. Damage was minimised by suspending services in ashy conditions (Magill et al., 2013).

2.4.4.3 Ports and ships

Lahars and PDCs can affect harbours or water bodies due to increased sedimentation. The most notable example occurred in the Columbia Shipping Canal, USA after the 1980 Mt. St. Helens eruption. Lahar deposits filled it and reduced its capacity by 85%, rendering the canal effectively unusable (Blong, 1984), effecting the economy in the Pacific Northwest. Lava flows have also affected ports, the best known event is the 1973 Eldfell eruption in Heimaey, Iceland. Lava threatened to block the harbour entrance, however, an extensive lava cooling operation successfully prevented this from occurring (Williams and Moore, 2008).

Ships may sustain damage, such as abrasion of moving parts and clogging of air filters and water intakes during tephra falls (T.M. Wilson et al., 2012). Vesiculated tephra (pumice and scoria) can float on water creating a pumice raft, which may be ingested into ships water intakes (T.M. Wilson et al., 2012) and/or disrupt shipping routes. There are instances of resilience, for example, during the 2008 eruption of Okmok Volcano, Alaska several boats received minor tephra fall with no impacts other than damage to one air filter (Neal et al., 2011).

2.4.4.4 Airports

Physical damage to airports

Volcanic flows can completely destroy airports if they are located near river valleys or flood plains. During the 1997 eruption of Soufrière Hills volcano, Montserrat, the W. H. Bramble Airport was overrun and completely destroyed by PDCs (Guffanti et al., 2009) (Figure 2.11). Likewise, after the 2008 eruption of Chaitén volcano, lahars completely buried the Chaitén airport runway and inundated many associated buildings; the airport subsequently closed (Pallister et al., 2010). A temporary airport runway was established on a widened road to restore flights to the area. The runway at Goma International

Airport, DRC was inundated by lava during the 2002 Nyiragongo eruption, reducing the runways length by 1 km, however it is still usable for smaller sized aircraft (Baxter and Ancia, 2002).

Damage to aircraft in flight is well documented and includes: loss of engine thrust as a result of tephra ingestion and adherence to turbine blades; and abrasion of turbine blades, windshields, leading edges, protruding probes and sensors. We refer the reader to Casadevall (1994), the International Civil Aviation Organization (2007), Guffanti et al. (2010), Dunn (2012) and Drexler et al. (2011) for comprehensive reviews of tephra related damage to aircraft.

Disruption to aviation

Trace (~1 mm) quantities of tephra deposited on runways, taxiways and aprons can reduce visibility, cause loss of traction, interrupt ground services and damage parked aircraft (Guffanti et al., 2009) (Figure 2.9A). When these impacts occur, airports typically close due to flying safety regulations leading to widespread disruption. Because such thin tephra deposits can close airports, airports located in distal areas may also be affected resulting in widespread airport closure and travel disruption. In addition, the presence of tephra in the atmosphere can force the closure of airspace or the re-routing of travel routes. For example, during the 2010 eruption of Eyjafjallajökull volcano, Iceland, European and North Atlantic airspace was closed for six days in April 2010 to prevent potential aircraft damage and limit risk to life (Sammonds et al., 2010).

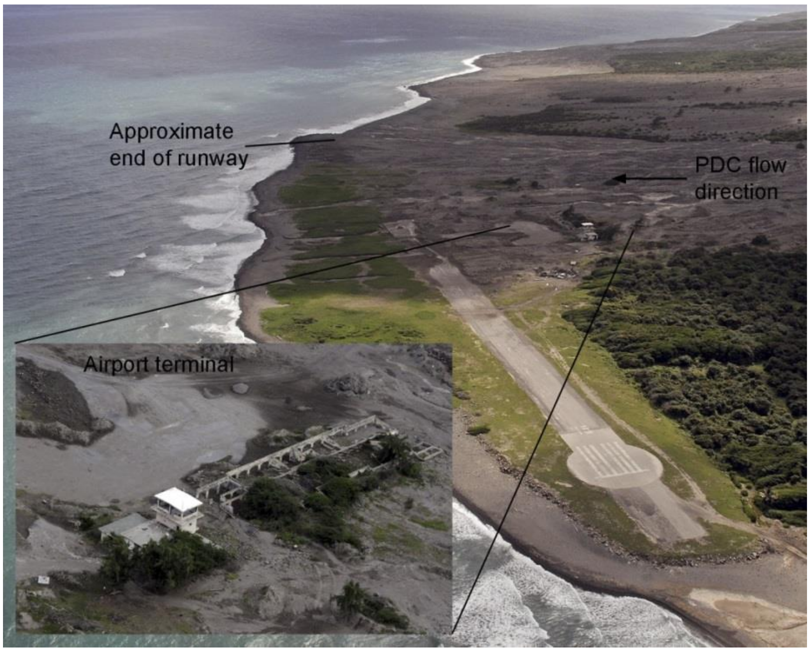


Figure 2.11: Burial and destruction of the runway and terminal building at the W. H. Bramble Airport, Montserrat by a PDC during the 1997 eruption of Soufrière Hills. The runway has since been completely buried and abandoned (Photos: Brian Digital).

2.4.5 Communication networks

Communication networks are typically expansive and comprise a wide range of components in a many different network configurations (Figure 2.8B).

2.4.5.1 Physical damage to communication equipment

Volcanic flows are likely to cause considerable damage to communication infrastructure (e.g., tower, poles, lines) if they are situated in flow paths or in areas close to the volcano, however evidence is scare. During the 1991 Unzen eruption, numerous utility poles were broken at their bases after being impacted by PDCs (Clarke and Voight, 2000).

2.4.5.2 Disruption to communication equipment

Theoretically tephra particles may cause communication signal attenuation and interference as it is known that dust storms cause this type of disruption (e.g., Saleh and Abuhdima, 2011). A review by Wilson et al. (2009) suggest tephra induced signal attenuation may preferentially affect low frequency (30–300 kHz) services. Signal interference has been reported during tephra falls from Pacaya volcano, Guatemala (Wardman et al., 2012a), Tungurahua volcano, Ecuador (Sword-Daniels et al., 2011), Mt. Hudson, Chile (Wilson et al., 2011) and Merapi volcano, Indonesia (Wilson et al., 2007) (Figure 2.9B), however these occurrences are poorly documented. In contrast, cellular and ultra high frequency networks and telemetered sites operated without interruption in Futaleufú, Chile, which received >150 mm of tephra during the 2008 Chaitén eruption (T.M. Wilson et al., 2012).

2.4.6 Critical components

We define critical components as those that are integral to most critical infrastructure sectors such as heating, ventilation and air conditioning (HVAC) systems and electronic equipment. HVAC systems are used in most critical infrastructure sectors for internal environmental control, and to also keep equipment within normal operating temperatures (T.M. Wilson et al., 2012).

2.4.6.1 Physical damage to critical components

The majority of HVAC and computing systems are physically small and therefore very likely to be completely destroyed and carried away by volcanic flows. In addition, the high temperatures of PDCs and lava flows will likely melt plastics and the wet nature of lahars will cause electrical short circuits. The only documented case that specifically mentions volcanic flow impacts to electronics is de Bélizal et al. (2013) who describe a lahar from Merapi volcano destroying a house in which all electronic equipment was lost and/or destroyed. Tephra particles can cause abrasive damage to moving components such as cooling fans, potentially resulting in fan failure. Abrasion is more likely to occur with fine tephra particles that can penetrate fan bearings and will occur over a long period of time (Barnard, 2009; G. Wilson et al., 2012).

2.4.6.2 Disruption to critical components

Filters and fans are particularly vulnerable to blockage from tephra fall as these components are in direct contact with the atmosphere (G. Wilson et al., 2012) (Figure 2.9B). These impacts may result in overheating and shutdown of HVAC and electronic equipment, causing disruption to services. During the 1992 Mt. Spurr, Alaska eruption, tephra fall (3 mm) blocked a number of HVAC system filters. Fortunately no electronic equipment overheated due to the cool ambient temperatures in Anchorage at the time (T.M. Wilson et al., 2012). Computers may also suffer from jamming of mechanical components and keyboards and overheating under a thick covering of tephra (Gordon et al., 2005; G. Wilson et al., 2012). Generally disruption appears to be temporary as once tephra has been removed from the components, functionality is restored (G. Wilson et al., 2012).

2.4.7 Buildings

Buildings and other similar structures can be impacted by all volcanic hazards considered here. Buildings may experience no or light physical damage through to complete destruction. We review structural damage from increased lateral and static loads, fire, abrasion and corrosion. We refer the reader to Baxter et al. (2005) and Jenkins et al. (2014a) for a detailed review of building impacts for tephra fall and PDC hazards.

2.4.7.1 Physical damage from lateral loads

Volcanic flows cause extensive damage to buildings located in and near flow paths (e.g., de Bélizal et al., 2013) (Figure 2.5). Historic eruptions at Vesuvius (79 CE) and Mt. Pelée, Martinique (1902) and recent eruptions at Mt. St. Helens (1980), Unzen volcano (1991) and Merapi volcano (1994, 2006, 2010) demonstrate that PDCs cause substantial damage to buildings and structures (Figure 2.5A). Lahars generated during and after the eruptions of Mt. Pinatubo (1991) and Chaitén (2008) flowed into populated areas, causing considerable destruction and burial of buildings (Janda et al., 1996; Pierson et al., 2013) (Figure 2.12) and large economic losses (Mercado et al., 1996). The principal damaging mechanism of these flows is increased lateral loads. If lateral loads are greater than the strength of a building's walls and roof (depending on the flow height) structural damage will result and in the worst case the building will collapse. Windows and doors are the most vulnerable components in a building as they have low resistance to lateral loads and are easily damaged by entrained debris impacts (Baxter et al., 2005; Spence et al., 2007). Shielding of buildings by topography and other buildings can affect damage distribution (Zuccaro and Ianniello, 2004).

Lava flows are less energetic than PDCs and lahars and cause damage to buildings due to their considerable mass and 'bulldozing' action (i.e., lava flows can push building over) (Figure 2.5B). Weaker buildings and those located in lava flow paths or on the flanks of the volcano are most vulnerable and sustain the highest degree of damage. Numerous volcanoes have produced lava flows that have caused damage to buildings, including Mt. Vesuvius, Mt. Etna, Nyiragongo volcano, Kilauea, Sakura-jima and Heimaey (Blong, 1984). Attempts have been made to lessen the impacts of lava flows through water cooling of flows (e.g., Heimaey, 1973: Williams, 1997) and by diverting flows with barriers (e.g., Mt. Etna, 2001: Barberi et al., 2003) with varying levels of success.

2.4.7.2 Physical damage from static loads

Tephra falls can cause damage to buildings by increased static load as a result of tephra accumulation (Figure 2.13). High intensity tephra falls (>100 mm) can increase the static load on a building's roof and if it exceeds the load carrying capacity, damage or collapse may occur (Spence et al., 1996) (Figure 2.13). Damage and indeed tolerance to damage is dependent on building typology and maintenance, tephra density, thickness and moisture content, as water will increase bulk density and therefore tephra load (Johnston, 1997). During the 1973 Heimaey eruption numerous houses with flat roofs suffered collapse following accumulation of ~1 m of dry tephra (Blong, 1984). In contrast, during the 1991 Mt. Pinatubo eruption, ~200 mm of wet tephra was sufficient to cause severe roof damage to ~50% of the building stock in the town of Castillejos, while the remaining 50% of buildings sustained no or minor damage (Spence et al., 1996). Tephra removal may exacerbate roof damage due to increased static load from people on the roof (Jenkins et al., 2014a). Buildings in close proximity to the volcano are most vulnerable to structure damage as this is commonly where high intensity tephra accumulations occur.

Non-structural components such as gutters and roof overhangs are vulnerable to increased static loads. Because these elements are not design to withstand large loads, they will sustain damage first during low intensity tephra fall.

2.4.7.3 Other impact mechanisms

Fire can also cause damage to buildings following PDCs, lava flows and hot tephra particles. PDCs comprise of hot gases and particles and if these infiltrate a building fires can be ignited. In addition, lava flows have temperatures above the ignition point of common construction materials and therefore can ignite fires causing damage to many buildings. In most cases if buildings are not destroyed by lava flow impact, they will be destroyed by fire (Blong, 1984). Flow deposits may also bury buildings causing further damage and preventing access (Figure 2.12). Abrasion of exterior elements such as windows and cladding may occur as a result of tephra falls, PDCs or lahars however damage is likely to be aesthetic. In addition, prolonged tephra exposure, in the presence of water, may cause corrosion damage to metal roofs and gutters (Oze et al., 2013).

Figure 2.12: Extensive damage to a school in Chaitén town, Chile from a lahar after the 2008 eruption of Volcán Chaitén. Two exterior walls have been completely removed and the ground around the foundations has been scoured. (C) Burial of a building, up to window level, in Chaitén town from a lahar after the 2008 eruption of Volcán Chaitén. A power pole is also damaged. (D) A building in Chaitén town, inundated by a lahar after the 2008 eruption of Volcán Chaitén (Photos: G Leonard).

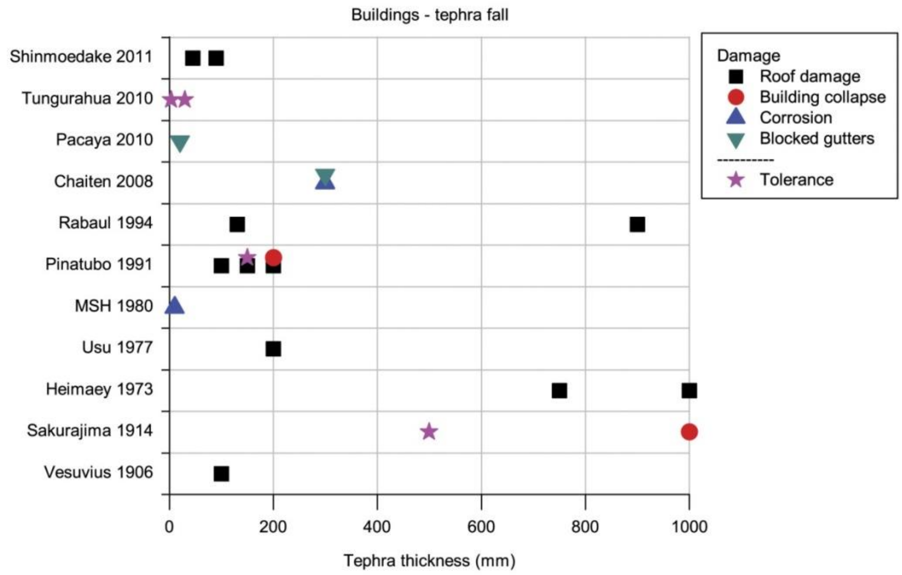


Figure 2.13: Summary of documented tephra fall impacts to buildings as a function of tephra thickness. Note: only data where tephra thickness is known or derived are plotted.

2.5 Characteristics of impacts to critical infrastructure

Empirical data of impacts to critical infrastructure presented above (Section 2.4) suggests that primary impacts occur on a continuum from causing disruption to complete damage (Figure 2.14). The hazard intensity window over which disruption and damage occurs is dependent on hazard type and characteristics, infrastructure design and any preparedness and response actions (Figure 2.14). However, disruption resulting from tephra fall, PDC and lahar hazards tends to occur at low hazard intensities where there is insufficient intensity to cause damage. Physical damage results at higher hazard intensities. In contrast, lava flows rarely cause disruption to critical infrastructure systems and tend to cause damage at all intensities (Figure 2.5). Secondary disruption will also result from physical damage to infrastructure components. A semi-quantitative analysis of infrastructure impacts (Figure 2.15), which draws upon impact data from Figures 2.4, 2.5, 2.7, 2.9 and 2.13 shows that tephra falls tend to cause disruption type impacts and less damage, while volcanic flows cause high levels of both damage and associated secondary disruption. The solid line in Figure 2.15 shows the 1:1 relationship between disruption and damage, with those infrastructure that plot above or below this line showing their tendency to preferentially cause one impact type over the other. A limitation of Figure 2.15 is that it assumes generic infrastructure design. There are numerous different components, designs and network configurations for such infrastructure systems which may vary within and between cities, regions and countries. Each different infrastructure design can influence vulnerability as each design will be tolerant to different hazard intensities.

In the following subsections we discuss the characterisation of impacts as causing disruption (Section 2.5.1) or damage (Section 2.5.2) based upon hazard types and intensities and infrastructure design. We explore how clean up, exclusion zones, infrastructure design and different hazard properties influence impact type and severity. We finish by developing impact scales, based on hazard intensity thresholds, to estimate vulnerability (Section 2.5.3.2).

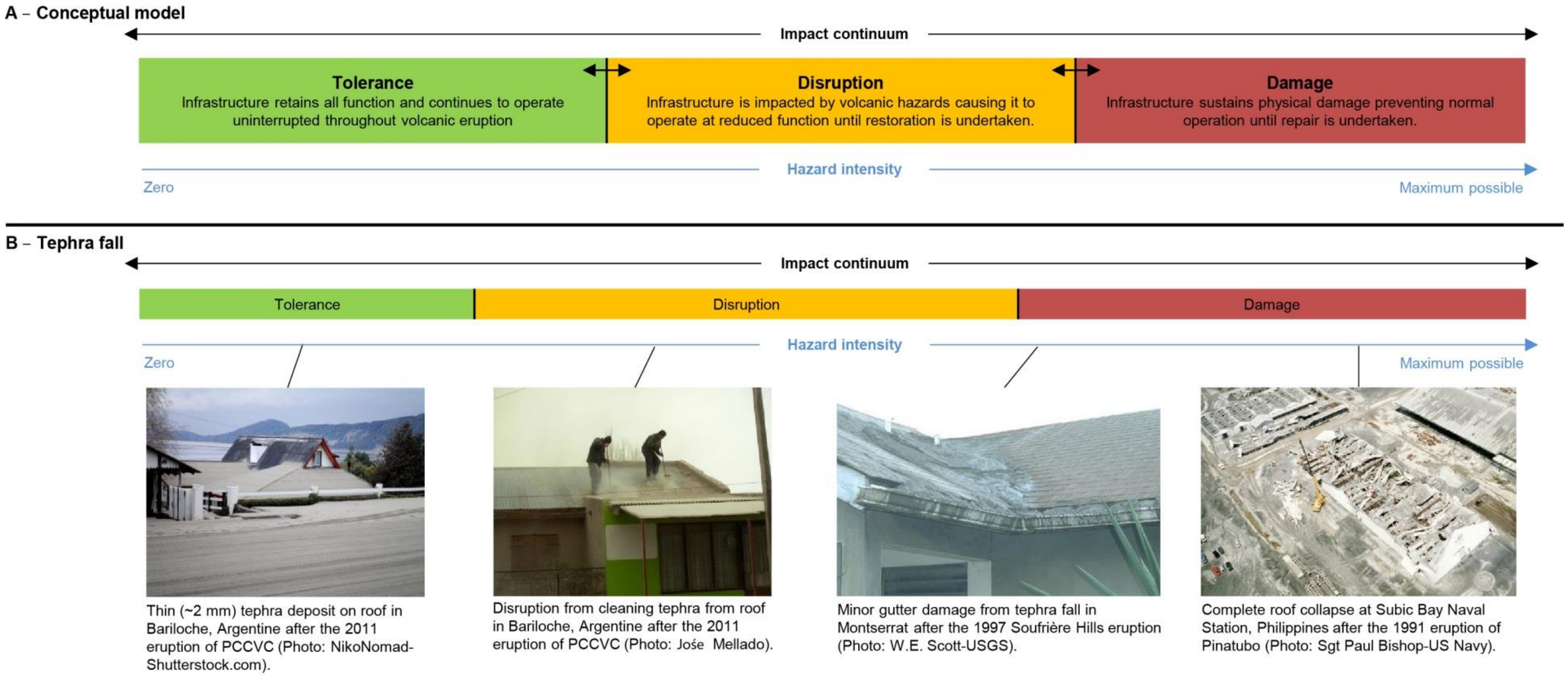


Figure 2.14: (A) Conceptual model of the continuum of impacts to critical infrastructure observed as a function of hazard intensity. Boundaries between impact severities (tolerance, disruption and damage) will occur at different hazard intensities for different volcanic hazards and for different critical infrastructure components and system designs. Generalised examples of the range of each impact severity (tolerance, disruption and damage) as a function of hazard intensity for (B) tephra falls, (C – following page) lahars and PDCs, and (D – following page) lava flows assuming generic infrastructure design.

C – Lahar & PDC

Impact continuum

Tolerance | Disruption | Damage

Hazard intensity

Zero — Maximum possible

Thin (~50 mm) lahar deposit on road in Chaitén town, Chile after the 2008 eruption of Chaitén. Road is still useable (Photo: G Leonard).

Thick PDC deposit on road preventing access after the 2006 eruption of Merapi, Indonesia (Photo: Wilson et al. 2007).

Severe damage of a bridge by lahars in 2011 after the 1999-2010 eruptions of Tungurahua, Ecuador (Photo: Sword-Daniels et al. 2011).

D – Lava flow

Impact continuum

Damage

Hazard intensity

Zero — Maximum possible

Lava flow covering and blocking the Chain of Craters road, Hawaii (Photo: Jasperdo).

House covered and destroyed by lava flows after the 2001 eruption of Mt Etna, Italy (Photo: Kemal Taner/Shutterstock.com).

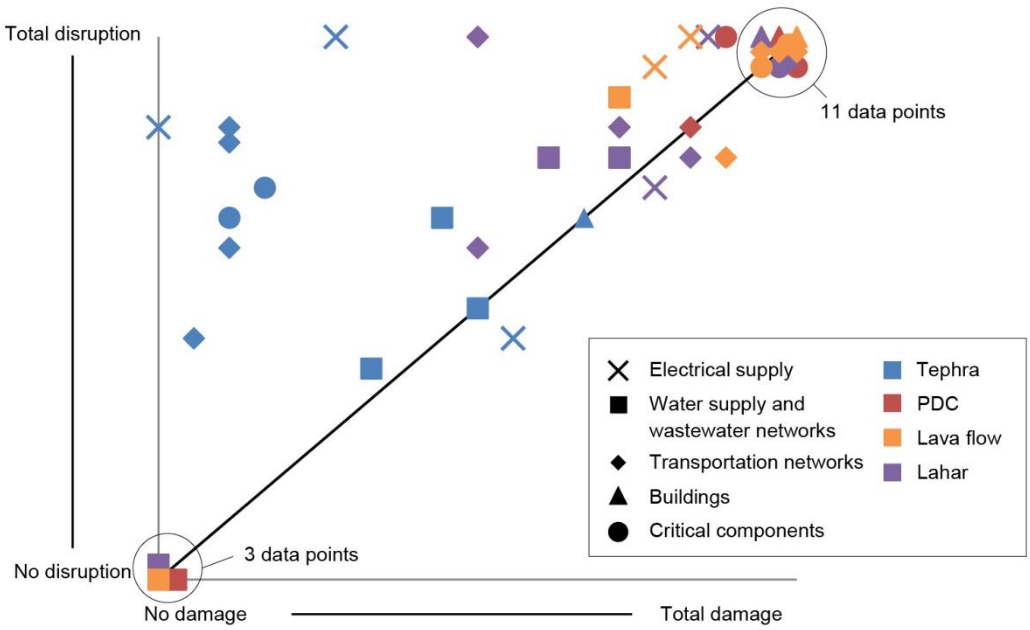


Figure 2.15: Relationship between critical infrastructure disruption and damage for investigated eruptions (1973–2011) as a result of tephra fall (blue), PDC (red), lava flow (orange) and lahar (purple). Black line shows an idealised 1:1 relationship between disruption and damage, where disruption are impacts that occur prior to the onset of physical damage and damage are impacts that occur as a result of direct physical damage (Section 2.4).

2.5.1 Disruption impacts to critical infrastructure

Disruption to critical infrastructure can occur as a result of direct interaction with volcanic hazards (Section 2.5.1.1), as a result of hazard clean-up operations (Section 2.5.1.2) and from restricted access with the implementation of emergency management exclusion zones (Section 2.5.1.3).

2.5.1.1 Critical infrastructure disruption from direct hazard impacts

Examining observed impacts (Section 2.4) and hazard intensity relationships (Figures 2.4, 2.5, 2.7, 2.9 and 2.13) it is evident that most infrastructure sectors can be disrupted by direct impact of tephra fall, PDCs and lahars. As Figure 2.14 shows, disruption tends to occur at low hazard intensities.

During low intensity tephra falls, there appears to be insufficient accumulated tephra mass to induce any increased static loading damage on these infrastructure components and tephra will simply accumulate on exposed components (Figure 2.6B). Likewise, for low intensity regions of PDCs and lahars (i.e., flow peripheries) there is insufficient dynamic pressure to cause physical damage to critical infrastructure (Baxter et al., 2005) and deposition will occur. The deposition of unconsolidated tephra in or on components will cause disruption and reduce function by causing blockages (e.g., air and water filters) or limiting access and preventing use of certain infrastructure such as buildings and transportation networks.

In addition, the presence of tephra particles in the atmosphere can cause significant and prolonged disruption for some infrastructure, particularly transportation networks as suspended tephra will reduce visibility and cause abrasion damage. For example, the 2010 eruption of Eyjafjallajökull, Iceland and subsequent closure of European and North American airpace for six days to prevent aircraft damage (Sammonds et al., 2010).

Infrastructure component and system design will also influence disruption. Components with no or few moving parts are unlikely to be damaged at low hazard intensities as tephra particles will not be lodged between moving parts; a primary cause of abrasion damage. However, these components will become covered in tephra limiting access and causing disruption. Systems with electrical components (e.g., insulators and electronic devices) may sustain short circuit faults in the presence of wet tephra (Wardman et al., 2012c), disrupting their operation. In addition, some infrastructure systems and components, such as road transportation and electrical insulators, are resilient to damage at all tephra hazard intensities and are likely to be disrupted at high hazard intensities (Figure 2.4 and 2.8A).

Some disruption may only affect the infrastructure operators. For example, after the 2011 PCCVC eruption, sand filters at the Bariloche water treatment plant required increased maintenance time for cleaning however during this time there were no water outages and services continued as normal (Wilson et al., 2013). In these instances, increased maintenance requirements will incur additional costs and may prevent operators from undertaking other tasks.

2.5.1.2 Critical infrastructure disruption during clean-up operations

Tephra falls, PDCs and lahars produce unconsolidated deposits that require removal and clean up to avoid ongoing and prolonged disruption or to reinstate critical infrastructure services (T.M. Wilson et al., 2012). Proper clean-up will reduce tephra remobilisation, minimise the potential for future damage (e.g., abrasion and corrosion) and human health effects which can result from inhalation of tephra particles (Horwell and Baxter, 2006). While it is possible for some infrastructure sectors to clean deposits from their equipment and sites without causing disruption (e.g., live cleaning of electrical networks), many sectors will have to partially or completely shut down (a controlled shut down) to undertake cleaning. Performing controlled shutdowns of all or parts of an infrastructure network will cause further disruption and prevent society from using these services. In many cases however, this is unavoidable as continued operation may result in physical damage of components leading to further disruption. Controlled shutdowns for cleaning purposes have been documented for electrical supplies to prevent continual flashover (Figure 2.4), water supplies to prevent water shortages and plant damage (Figure 2.7A) and at airport runways to prevent aircraft damage and tephra remobilisation (Figure 2.9A). Ultimately the decision to clean up unconsolidated deposits and/or initiate controlled shutdowns will be dependent on hazard intensity but also on the operational practices of the particular infrastructure operators.

2.5.1.3 Critical infrastructure disruption in exclusion zones

Disruption to critical infrastructure can occur without the presence of any volcanic hazards through the implementation and enforcement of evacuation and exclusion zones by emergency management authorities. Generally these zones will be developed for flow hazards, as these are more dangerous that tephra fall. Zones may be implemented prior to the onset of an eruption or during an eruption to prevent loss of life in dangerous areas. If infrastructure networks or sites are located within these zones, services are likely to be disrupted as personnel will not be able to access these areas. For example, during the eruption of Montserrat (1995–ongoing) and the subsequent destruction of Plymouth, the water utility had to move some of the springs and wells which were located inside the exclusion zone (Sword-Daniels et al., 2014). If infrastructure within an exclusion zone is damaged it is unlikely that personnel will be able to enter to perform repairs unless an agreement is made with emergency management officials.

2.5.2 Physical damage to critical infrastructure

All volcanic hazards considered here can cause physical damage to critical infrastructure sectors and components. Physical damage has been observed occurring at all intensity levels for PDCs, lahars and lava flows (Figure 2.5) and at high intensity tephra falls (Figures 2.4, 2.5, 2.7, 2.9 and 2.13).

Abrasion damage can occur to any exposed element as a result of contamination with tephra particles or from passing PDCs and lahars. Components with moving parts such as water and wastewater pumps, electrical switches, cooling fans are more vulnerable as tephra particles may become lodged between moving surfaces. Abrasion damage to pumps has been documented for water supply and wastewater networks at tephra thicknesses of >30 mm and >4 mm, respectively (Figure 2.7). While these reports document the tephra thickness at which damage occurred, hazard exposure time, which is a primary control for abrasion severity, is not documented. Likewise, corrosion of metal surfaces, particularly building roofs (Figure 2.13), also occurs over time. In addition, increasing tephra thickness will increase corrosion severity as more acidic tephra leachates will be delivered to the roof surface (Oze et al., 2013).

At higher tephra fall intensities structural damage can occur due to increased static loading. Most observed tephra-induced structural damage has occurred to buildings (residential and commercial) and their roofs (Figure 2.13), as research has tended to focus on occupant safety. However, tephra accumulations on other exposed infrastructure components (e.g., electrical substation gantries, water storage and treatment tanks) are likely to cause structural damage if the load exceeds the structure's strength. Damage severity is influenced by tephra density and moisture content as these parameters increase so does the static load on the structure (Macedonio and Costa, 2012; Jenkins et al., 2014a). Damage to non-structural elements is likely to occur first as they are inherently weaker than engineered structural components.

PDCs, lahars and lava flows cause physical damage at all hazard intensities (Figure 2.5). The primary damage mechanism is increased dynamic pressures which overcome structural design causing structures to fail. PDCs and lahars become rapidly less energetic with increasing distance from vent and flow axis (Spence et al., 2004b; Jenkins et al., 2013) and higher damage severity is expected in flow paths and river valleys and in proximal areas (Baxter et al., 2005). However, damage assessments of Baxter et al. (2005) and Jenkins et al. (2013) suggest that dynamic pressures can vary between ~1–5 kPa within tens of meters, resulting in non-uniform building damage. For most infrastructure sectors there is a lack of data (Figure 2.5) regarding gradations in damage severity and therefore as a first order approximation, we assume a binary impact model, where damage is predicated on the presence of a volcanic flow(s). However for building damage there is sufficient impact data (e.g., Spence et al., 2004a; Baxter et al., 2005; Jenkins et al., 2013) to assess gradational damage.

Lava flows and sufficiently hot PDCs will cause fire damage to combustible structures and materials. Once a structure is ignited it will generally be completely destroyed by fire; for most structures, the benefit of extinguishing the fire is far outweighed by life safety concerns that would be encountered in an attempt. Buildings, structures and infrastructure (e.g., transportation routes) will become inundated and covered by volcanic flows, resulting in disruption or permanent damage, especially for lava which will solidify once cooled.

2.5.3 Estimating critical infrastructure vulnerability

Estimating vulnerability of critical infrastructure to volcanic eruptions can be difficult due to the number of facets that influence vulnerability and resilience. By reviewing empirical data (Figures 2.4, 2.5, 2.7, 2.9 and 2.13) relationships between disruption and/or damage and hazard intensity (Section 2.5.3.1) can be estimated and presented using impact scales (Section 2.5.3.2). When assessing vulnerability, consideration must also be given to the interactions between multiple volcanic hazards (Section 2.5.3.3).

2.5.3.1 Hazard intensity metrics

Volcanic hazards have a number of different hazard properties which can cause disruption and damage. This is in contrast to other natural hazards where there are generally few hazard properties which contribute to disruption and damage. For example, the principle damaging property of earthquakes is ground shaking, commonly assessed by peak ground acceleration, whereas PDCs can cause damage through lateral loading (dynamic pressure) and fire (temperature). We define these properties collectively as hazard intensity metrics (HIM). When assessing vulnerability a single HIM may not accurately capture all of the impactful attributes a hazard has to a particular infrastructure sector. To this end, Tables 2.8–2.11 present the relative relevance of different HIMs for each volcanic hazards and infrastructure sector and provide an indication on whether these are strong empirical relationships or theoretical. Selection of a HIM for vulnerability and risk assessment should consider: (1) the HIMs appropriateness to accurately describe a range of impact severity; (2) the ease of HIM measurement in the field or laboratory; and (3) the applicability of the HIM to hazard model outputs. The most appropriate and commonly used HIM candidates are thickness or mass loading (tephra fall), dynamic pressure (PDC), flow height (lava flow) and flow velocity (lahar), however different HIMs can be used depending on the impact(s) and infrastructure sector(s) of interest.

2.5.3.2 Disruption and damage states

To classify and categorise impacts to critical infrastructure a common impact scale can be used (Blong, 2003b) which includes disruption and damage states. In volcanology, impact scales are available for building damage from tephra fall (e.g., Spence et al., 1996; Blong, 2003a) and PDC impacts (e.g., Spence et al., 2004b; Baxter et al., 2005). Here we expand impact scale coverage to include critical infrastructure sectors examined in Section 2.4 for tephra fall, lava flow, PDC and lahar hazards (Tables 2.12–2.15). We define four common impact states (IS): IS_0, no damage; IS_1, cleaning required; IS_2, repair required; and IS_3, replacement or financially expensive repair. Four levels were chosen because empirical impact data across a range of ISs was lacking for most infrastructure and therefore further subdivision was not justified. Separate descriptions for disruption and physical damage are provided to reflect impact dichotomy presented in Sections 2.5.1 and 2.5.2. For each impact scale (Tables 2.12–2.15) the most diagnostic HIM, based on its relationship with empirically observed impacts, was used, these are: thickness (tephra fall); dynamic pressure (PDC); flow depth (lava flow); and flow velocity (lahar) (Tables 2.8–2.11). Intensity thresholds were derived by categorising empirical impact data in Figures 2.4, 2.5, 2.7, 2.9 and 2.13 and Section 2.4 and by using expert judgement to indicate anticipated impacts where data was lacking, primarily at high hazard intensities.

For tephra fall (Table 2.12), different intensity thresholds were derived for each critical infrastructure sector because each sector responds differently given a specific hazard intensity. For example, ~1 mm of tephra will close an airport while this tephra thickness will not cause any damage to a building. Differences in how infrastructures respond to tephra fall precluded the use of generic tephra fall thresholds which would be applicable to all infrastructure sectors. In contrast, for PDCs and lahars (Tables 2.13 and 2.15) we consider impacts to be binary for all infrastructure sectors except buildings. While there may be gradational infrastructure impacts from PDCs and lahars at flow margins (see Section 2.5.2) we found insufficient empirical evidence to derive hazard thresholds for intermediary impact states. Intermediary impact states for building damage are included and are drawn from the existing scales of Baxter et al. (2005) and Spence et al. (2004b). For lava flow hazards we consider impacts to be binary for all infrastructure sectors (Table 2.14) based on the destructiveness of lava flows.

Caution is urged when using our impact scales (Tables 2.12–2.15) as a number of assumptions have been made, such as: generic infrastructure design and typology, one discrete hazard occurrence and no mitigation actions taken by infrastructure operators. These scales should only be used either as guides or at regional scale vulnerability and risk assessment. Whenever possible, local vulnerability studies which account for each system's vulnerability characteristics should be undertaken first.

Table 2.8: Relevant tephra fall hazard intensity metrics for each infrastructure sector. Abbreviations are: E – strong empirical bases (numerous post-eruption and analytical data); e – weak empirical bases (few post-eruption data); *T* – strong theoretical bases (likely to be relevant but no post-eruption data); and *t* – weak theoretical bases (may be relevant). Refer to Table 2.1 for definitions of hazard intensity metrics.

Critical infrastructure sector	Tephra fall hazard intensity metrics							
	Thickness	Static load	Particle density	Surface chemistry	Grainsize	Moisture content	Hardness (abrasiveness)	Atmospheric concentration
Electrical supply								
Generation	E			E	e	e	E	
Transmission	E	e		E	e	E		*t*
Water supply network								
Source	E		*T*	E	e		*T*	
Treatment	E	*T*	E	E	E		E	
Buried network	*t*		*t*		*t*		E	
Wastewater network								
Treatment	E	*T*	E	e	E		E	
Buried network	*t*		*T*		*t*		E	
Transportation network								
Road	E	*t*		e	e		e	e
Air	E	*t*		*t*	e		E	E
Rail	E	*t*		*t*	e		*T*	e
Sea	e	*t*	E	*t*	e		e	*T*

Buildings	E	E	e	*T*	e	*T*	
Communication systems	e	*T*					e
Critical components							
HVAC	E		*T*	E	e	e	*T*
Electronics	E		e	E	E	e	*T*

Table 2.9: Relevant lava flow hazard intensity metrics for each infrastructure sector. Abbreviations are: E – strong empirical bases (numerous post-eruption and analytical data); e – weak empirical bases (few post-eruption data); *T* – strong theoretical bases (likely to be relevant but no post-eruption data); and *t* – weak theoretical bases (may be relevant). Refer to Table 2.1 for definitions of hazard intensity metrics.

Critical infrastructure	Lava flow hazard intensity metrics					
	Presence of lava	Depth of flow	Dynamic pressure	Velocity	Temperature	Cooling duration
Electrical supply						
Generation	*T*	*T*	*T*	*T*		
Transmission	e	e	*T*	*T*		
Water supply network						
Source	*T*	*t*	*t*	*t*		
Treatment	*T*	*t*	*t*	*t*		
Buried network	e	E				
Wastewater network						
Treatment		*T*	*T*	*T*		
Buried network	*t*					

Transportation network						
Road	E	E				*T*
Air	E	E				*T*
Rail		E				
Sea	E	E				
Buildings	E	E	E	E	E	
Communication systems	*T*	*T*	*T*	*T*		
Critical components						
HVAC	*T*	*T*	*t*	*t*		
Electronics	*T*	*T*		*t*		

Table 2.10: Relevant PDC hazard intensity metrics for each infrastructure sector. Abbreviations are: E – strong empirical bases (numerous post-eruption and analytical data); e – weak empirical bases (few post-eruption data); *T* – strong theoretical bases (likely to be relevant but no post-eruption data); and *t* – weak theoretical bases (may be relevant). Refer to Table 2.1 for definitions of hazard intensity metrics.

Critical infrastructure sector	PDC hazard intensity metrics			
	Dynamic pressure	Velocity	Temperature	Thickness of deposit
Electrical supply				
Generation	*T*	*T*		*T*
Transmission	E	E	*t*	*t*
Water supply network				
Source	E	E		*T*
Treatment	*T*	*T*		*t*
Buried network	e		*t*	
Wastewater network				
Treatment	*T*	*T*		*t*
Buried network				
Transportation network				
Road	E		*T*	e
Air	E		*T*	*t*
Rail	*T*			*t*
Sea	*t*			*t*
Buildings	E	E	E	e
Communication systems	E	E		*t*
Critical components				
HVAC	*T*	*T*		*T*
Electronics	*t*	*T*	*T*	*T*

Table 2.11: Relevant lahar hazard intensity metrics for each infrastructure sector. Abbreviations are: E – strong empirical bases (numerous post-eruption and analytical data); e – weak empirical bases (few post-eruption data); *T* – strong theoretical bases (likely to be relevant but no post-eruption data); and *t* – weak theoretical bases (may be relevant). Refer to Table 2.1 for definitions of hazard intensity metrics.

Critical infrastructure sector	Lahar hazard intensity metrics			
	Dynamic pressure	Velocity	Thickness of deposit	Depth of flow
Electrical supply				
Generation	*T*	*T*	*T*	
Transmission	E	E	*t*	e
Water supply network				
Source	*T*	*T*	*T*	
Treatment	*T*	*T*	*t*	*t*
Buried network	e	e		
Wastewater network				
Treatment	*T*	*T*	*t*	*t*
Buried network	*t*	*t*		
Transportation network				
Road	E	E	E	
Air	*T*	*T*	E	
Rail	E	E	*T*	
Sea	*t*	*t*	e	

Buildings	E		E	E
Communication systems	*T*	*T*	*t*	*t*
Critical components				
HVAC	*T*	*T*	*T*	
Electronics	e	e	e	

Table 2.12: Proposed impact states (IS) for expected impacts to critical infrastructure as a function of tephra fall thickness (mm). Disruption and damage descriptions and threshold values are subject to uncertainty and assume generic infrastructure design. Italicised threshold values indicate where expert judgment was used to derive theoretical estimates of when disruption and damage would occur. Disruption and damage at higher intensities (IS_3) include those at lower intensities (IS_1).

Sector	**Level** Description	**IS$_0$** No damage	**IS$_1$** Cleaning required	**IS$_2$** Repair required	**IS$_3$** Replacement or financially expensive repair
Electrical supply	**Threshold (mm)**	**<3**	**3–10**	**10–*100***	***>100***
	Damage	No damage	Possible abrasion to some moving parts, infiltration of tephra into substation gravel.	Damage to exposed equipment especially those with moving parts, possible electrical line breakage.	Structural damage to some equipment at generation and transmission/distribution sites, irreparable damage to moving parts (e.g., hydro power turbines).
	Disruption	No disruption	Temporary disruption to service caused by insulator flashover, cleaning and repair.		Widespread disruption to electrical supply with possible permanent disruption.
Water supply network	**Threshold (mm)**	**<1**	**1–20**	**20–*100***	***>100***
	Damage	No damage	Possible clogging of filters and some abrasion to moving components.	Damage to pumping equipment, other moving parts and infilling of tanks.	Collapse of reservoir roofs and infilling of open reservoirs and tanks.
	Disruption	No disruption	Normal operation with increased frequency of filter cleaning and increased turbidity.	Contamination of water and increased treatment required. Possible water use restrictions.	Severe contamination of water supply and exhaustion of supply due to damage and/or increased demand.
Wastewater network	**Threshold (mm)**	**<3**	**3–*10***	***10–50***	***>50***
	Damage	No damage	Possible minor abrasion to pumps, clogging of filters	Large amounts of sedimentation in network	Widespread sedimentation throughout entire network causing

Sector	Level	IS_0	IS_1	IS_2	IS_3
			and possible interference with chemical treatment process.	some causing blockages, some damage to treatment plant components and possible infilling of open tanks.	some blockages, irreparable damage to pumps and extensive structural damage to treatment plant components.
	Disruption	No disruption	Reduced capacity, operation with increased cleaning of filters.	Temporary disruption to service to unblock network and clean tanks possibly resulting in discharge of untreated sewage.	Long term to possible permanent disruption to service. Unable to treat wastewater, discharge of untreated sewage.
Airport	**Threshold (mm)**	**<1**	***1–30***	***30–150***	***>150***
	Damage	No damage	Possible abrasion of runway and apron markings and possible abrasion of paved surfaces.	Moderate abrasion of paved surfaces and landing lights.	Complete burial.
	Disruption	Airport open	Airport closure, reduced visibility.		Possible permanent closure.
Road	**Threshold (mm)**	**<2**	***2–50***	***50–150***	***>150***
	Damage	No damage	Possible abrasion of road markings and possible abrasion of paved surfaces.	Moderate abrasion of paved surfaces, weak bridges may experience structural damage.	Complete burial, structural damage to some bridges.
	Disruption	No disruption	Reduced visibility, loss of traction, covering of markings and possible road closure.	Roads impassable for 2WD vehicles. Dangerous driving conditions.	Roads impassable if tephra is unconsolidated, compacted tephra may be driven on by 4WD vehicles. Widespread road closures.
Rail	**Threshold (mm)**	**<1**	***1–30***	***30–150***	***>150***
		No damage	Possible abrasion and/or corrosion of railway tracks and signals, jamming of mechanical signals and contamination of		Complete burial

Sector	**Level**	**IS_0**	**IS_1**	**IS_2**	**IS_3**
			track ballast.		
		No disruption	Reduced visibility, signals and communications disrupted.	Loss of traction and possible derailing.	Impassable.
Marine	**Threshold (mm)**	**<1**	**1–*30***	***30–150***	***>150***
		No damage	Possible abrasion of paved surfaces.	Moderate abrasion of paved surfaces, pumice rafts covering the water surface.	Complete burial of paved surfaces.
		No disruption	Reduced visibility on land and sea.	Ship movements obstructed by pumice rafts.	Inoperable.
Vehicles	**Threshold (mm)**	**<3**	**3–*30***	***30–100***	***>100***
	Damage	No damage	Possible abrasion and/or corrosion to windshields, paintwork, aircraft leading edges, moving parts and clogging of air filters.	Extensive abrasion of moving parts and possible seizing of engines.	Extensive damage that is uneconomical to repair.
	Disruption	No disruption	Infiltration of tephra into personal compartments.	Frequent fluid and filter replacement and possible cleaning and reconditioning of engines.	Completely inoperable.
Communications	**Threshold (mm)**	**<5**	**5–*30***	***30–100***	***>100***
	Damage	No damage	No damage	Blockage and shutdown of cooling systems and damage to exposed components (e.g., dishes, towers, lines).	Structural damage to communication components (e.g., dishes, towers, lines).
	Disruption	No disruption	Overloading of	Temporary disruption to	Permanent disruption.

Sector	**Level**	**IS_0**	**IS_1**	**IS_2**	**IS_3**
			communication network from high demand and possible signal attenuation and interference.	service due to shutdowns and cleaning.	
Buildings	**Threshold (mm)**	**<10**	**10–100**	**100–*500***	***>500***
	Damage	No damage	Light roof damage and gutter damage and possible abrasion to windows and cladding.	Severe roof damage, damage to vertical structure, possible partial collapse.	Complete roof collapse and severe damage to rest of building.
	Disruption	Occupied	Infiltration of tephra into building and able to be occupied.	Large volumes of tephra inside building as well as parts of the structure, uninhabitable.	Beyond economic repair and uninhabitable.
Critical components	**Threshold (mm)**	**<1**	**1–10**	**10–*50***	***>50***
	Damage	No damage	No damage	Abrasion of moving parts and blockage of filters.	Extensive damage to most components.
	Disruption	No disruption	Reduced function until cleaned.	Reduced function and temporary shutdowns until cleaned.	Uneconomic to repair, disruption to service until replaced.

Table 2.13: Proposed impact states (IS) for expected impacts to critical infrastructure as a function of PDC dynamic pressure (kPa). Disruption and damage descriptions and threshold values are subject to uncertainty and assume generic infrastructure design. Impacts to most infrastructure are considered binary (See Section 4.2) thus there are no descriptions for IS_1 or IS_2 except for buildings where there is additional empirical data. Italicised threshold values indicate where expert judgment was used to derive theoretical estimates of when disruption and damage would occur.

Sector	**Level** Description	**IS_0** No damage	**IS_1** Cleaning required	**IS_2** Repair required	**IS_3** Replacement or financially expensive repair
Electrical supply	**Threshold (kPa)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Destruction of transmission and distribution lines, poles, towers and substations and damage to generation sites.
	Disruption	No disruption	–	–	Permanent disruption to service.
Water supply network	**Threshold (kPa)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes and infilling of uncovered water sources.
	Disruption	No disruption	–	–	Permanent disruption to service.
Wastewater network	**Threshold (kPa)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes, infilling of ponds and blockage of drains.
	Disruption	No disruption	–	–	Permanent disruption to service.
Transport	**Threshold (kPa)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Complete burial and heat damage of paved surfaces and railways. Destruction of some bridges. Infilling of harbours.
	Disruption	No disruption	–	–	Roads and rail impassable and widespread closures.

Sector	Level	IS_0	IS_1	IS_2	IS_3
Vehicles	**Threshold (kPa)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Vehicles buried, extensively damaged by pressure and heat and swept away.
	Disruption	No disruption	–	–	Completely inoperable.
Communications	**Threshold (kPa)**	**<0**	**–**	**–**	**>0**
	Damage		–	–	Destruction of ground level components (e.g., lines, cabinets, exchanges).
	Disruption	No disruption	–	–	Permanent disruption and signal interference caused by pyroclastic surges.
Buildings	**Threshold (kPa)**	**<1**	**1–10**	**10–*25***	***>25***
	Damage	No damage	Openings damaged, possible internal fire damage, external fire damage, sandblasting of walls and some damage to weak masonry.	All opening damaged, missile impacts evident and partial collapse of walls and/or roof, extensive internal fire damage.	Complete damage to building with few structural elements remaining.
	Disruption	Occupied	Infiltration of tephra, missiles and building material into building and fire damage making it uninhabitable.		Beyond economic repair and uninhabitable.
Critical components	**Threshold (kPa)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Complete destruction of exposed electronic equipment with most being swept away and/or buried and melting of plastic components.
	Disruption	No disruption	–	–	No functionality and uneconomic to repair.

Table 2.14: Proposed impact states (IS) for expected impacts to critical infrastructure as a function of lava flow depth (m). Disruption and damage descriptions and threshold values are subject to uncertainty and assume generic infrastructure design. Impacts to all infrastructure are considered binary (See Section 4.2) thus there are no descriptions for IS_1 or IS_2.

Sector	**Level** Description	**IS_0** No damage	**IS_1** Cleaning required	**IS_2** Repair required	**IS_3** Replacement or financially expensive repair
Electrical supply	**Threshold (m)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Destruction of transmission and distribution lines, poles, towers and damage a burial of substations and generation sites.
	Disruption	No disruption	–	–	Permanent disruption to service.
Water supply network	**Threshold (m)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes and infilling of uncovered water sources.
	Disruption	No disruption	–	–	Permanent disruption to service.
Wastewater network	**Threshold (m)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes, infilling of ponds and burial of drains.
	Disruption	No disruption	–	–	Permanent disruption to service.
Transport	**Threshold (m)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Complete burial heat damage to paved surfaces and railways.
	Disruption	No disruption	–	–	Transportation routes impassable resulting in permanent closure.
Vehicles	**Threshold (m)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Vehicles buried and burnt.
	Disruption	No disruption	–	–	Completely inoperable.

Sector	**Level**	**IS_0**	**IS_1**	**IS_2**	**IS_3**
Communications	**Threshold (m)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Destruction and burial of ground level components (e.g., lines, cabinets, exchanges).
	Disruption	No disruption	–	–	Permanent disruption.
Buildings	**Threshold (m)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Complete fire damage to building and burial.
	Disruption	Occupied	–	–	Beyond economic repair and uninhabitable.
Critical components	**Threshold (m)**	**<0**	–	–	**>0**
	Damage	No damage	–	–	Complete destruction and burial of exposed electronic equipment and melting of plastic components.
	Disruption	No disruption	–	–	No functionality and uneconomic to repair.

Table 2.15: Proposed impact states (IS) for expected impacts to critical infrastructure as a function of lahar velocity (m/s). Disruption and damage descriptions and threshold values are subject to uncertainty and assume generic infrastructure design. Impacts to most infrastructure are considered binary (See Section 4.2) thus there are no descriptions for IS_1 or IS_2 except for buildings where there is additional empirical data. Italicised threshold values indicate where expert judgment was used to derive theoretical estimates of when disruption and damage would occur.

Sector	**Level** Description	**IS_0** No damage	**IS_1** Cleaning required	**IS_2** Repair required	**IS_3** Replacement or financially expensive repair
Electrical supply	**Threshold (m/s)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Destruction of transmission and distribution lines, poles, towers and substations and damage to generation sites (e.g., abrasion to hydro power turbines).
	Disruption	No disruption	–	–	Permanent disruption to service.
Water supply network	**Threshold (m/s)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Damage to treatment facilities, above-ground pipes and water intake structures and infilling of uncovered water sources.
	Disruption	No disruption	–	–	Permanent disruption to service due to damage and severe contamination.
Wastewater network	**Threshold (m/s)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes, infilling of ponds and blockage of drains.
	Disruption	No disruption	–	–	Permanent disruption to service.
Transport	**Threshold (m/s)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Complete burial and erosion damage to paved surfaces and railways. Destruction of some bridges and scour of embankments. Infilling of harbour.
	Disruption	No disruption	–	–	Transportation routes impassable resulting in permanent closure.

Sector	Level	IS_0	IS_1	IS_2	IS_3
Vehicles	**Threshold (m/s)**	**<0**	–	–	**>0**
	Damage	No damage	–	–	Vehicles buried, extensively damaged by pressure and swept away.
	Disruption	No disruption	–	–	Completely inoperable.
Communications	**Threshold (m/s)**	**<0**	–	–	**>0**
	Damage	No damage	–	–	Destruction of ground level components (e.g., lines, cabinets, exchanges).
	Disruption	No disruption	–	–	Permanent disruption.
Buildings	**Threshold (m/s)**	**<1**	***1–3***	***3–5***	***>5***
	Damage	No damage	Damage to openings and non-structural elements and infilling of building interior with debris.	Moderate structural damage to walls, some partially collapse.	Complete damage to building with few structural elements remaining and/or swept off foundations.
	Disruption	Occupied	Infiltration of debris and building material into building making it uninhabitable.		Beyond economic repair and uninhabitable.
Critical components	**Threshold (m/s)**	**<0**	**–**	**–**	**>0**
	Damage	No damage	–	–	Complete destruction of exposed electronic equipment with most being swept away and/or buried.
	Disruption	No disruption	–	–	No functionality and uneconomic to repair.

2.5.3.3 Interactions between volcanic hazards

During a volcanic eruption multiple hazardous phenomena often occur simultaneously or in short succession. This is caused by changes in eruption style (from effusive to explosive or from explosive to effusive), during explosive eruptions or as a result of multiple vents erupting simultaneously. The interaction and impact of multiple volcanic hazards on critical infrastructure may lead to different vulnerability outcomes compared to single hazard impacts. However, multiple volcanic hazard impacts are rarely studied because of the increased complexity of hazard and infrastructure interactions.

One study that addresses multi-volcanic hazard impacts is Zuccaro et al. (2008). They investigate impacts on residential buildings from tephra fall with simultaneous earthquakes or PDCs for a simulated Mt. Vesuvius eruption. For the combination of tephra fall and earthquake a decrease in the seismic response of the building was observed, i.e., the building is more susceptible to earthquake damage if tephra is deposited on the roof. For the scenario of tephra fall followed by a PDC, Zuccaro et al. (2008) found that the vertical load exerted on the roof from tephra fall provided a stabilising effect when the building was impacted by a PDC. While this approach estimated building vulnerability it could also be applied to critical infrastructure. Multi-volcanic hazard research should be advanced to develop vulnerability assessments for volcanic eruptions and/or scenarios rather than just specific individual volcanic hazards.

2.6 Future direction

2.6.1 Implications for volcanic risk assessment

Over the past few decades there has been an emphasis on understanding, quantifying and modelling volcanic hazards. This has produced a number of high quality empirical, physical and probabilistic models which evaluate occurrence probabilities and spatial extents of various volcanic hazards (e.g., Schilling, 1998; Bonadonna, 2006; Charbonnier and Gertisser, 2009; Wadge, 2009; Marzocchi et al., 2010; Jenkins et al., 2012). These models have contributed to a detailed understanding of volcanic hazards and have greatly improved the contribution of volcanology science to disaster risk reduction and management.

At present, volcanic vulnerability and comprehensive risk assessments are less advanced than hazard assessments (Section 2.3), however the contributions of Blong (1984), Spence et al. (1996), Blong (2003a), Baxter et al. (2005), Wardman et al. (2012c), T.M. Wilson et al. (2012) and Jenkins et al. (2014a) have progressively increased and broadened the knowledge of volcanic impact occurrence, damage mechanisms, mitigation strategies and emergency management response. While these studies go a long way towards improved vulnerability assessment, collectively they have not progressed to the point of developing robust quantitative vulnerability models to inform land-use planning and infrastructure design codes (perhaps with the exception of residential buildings). Additionally, lack of awareness of volcanic impacts in critical infrastructure mitigation strategies, such as citing, design and contingency planning rarely, if ever, consider volcanic hazards. Whilst land-use planning and engineering design might not be appropriate in all situations it is appropriate for sensitive and/or high value infrastructure, such as nuclear power stations. For example, the International Atomic Energy Agency initiative (IAEA, 2013) has considered volcanic hazards in site evaluation at nuclear power installations. The NZ VISG science/industry collaboration is also an example of critical infrastructure organisations supporting and using volcanic resiliency research to reduce risk (Wilson et al., 2014). And global awareness is increasing with the inclusion of volcanic hazards for the first time in the Global Assessment Report on Disaster Risk Reduction 2015 (Jenkins et al., 2014b). Engineering design, often implemented at little extra cost, and effective contingency planning is likely to offer substantial societal benefits through reduced infrastructure service downtime and restoration costs. A cost-benefit analysis would be the next step to investigate the value of such mitigation strategies.

2.6.2 Goals for the next 10 to 25 years

Reducing the impacts of volcanic eruptions on society is the ultimate goal of volcanic risk management. Population growth, land-use pressure and society's increasing expectation of infrastructure performance during and after disasters will make this a challenge for critical infrastructure operators.

To progress towards increased critical infrastructure resilience, a crucial first step is for infrastructure operators to include volcanic hazards as a risk routinely managed. A value proposition is required where scientists and operators identify and establish the risk context and demonstrate the value of risk mitigation. The scientific community must support this collaboration through producing the best possible quality hazard, vulnerability and risk information to support risk mitigation and management. Broad and in-depth understanding of direct and indirect impacts from all credible volcanic hazards and hazard intensities is required. By first understanding the intensity at which impacts occur for different critical infrastructure components and the resulting impact severity enables decisions to be made about the most appropriate mitigation strategy for the particular situation; whether it be land-use planning, infrastructure design or contingency planning. To improve volcanic vulnerability assessments, the volcanology community in partnership with engineers, infrastructure operators, risk and continuity managers, and the communities which rely on critical services, need to identify safe and acceptable levels of critical infrastructure performance during volcanic crises by robustly analysing existing impact data and seeking additional quantitative empirical and theoretical data. Continued investment in research to identify and refine vulnerability (or conversely resilience) of critical infrastructure requires continued field observations, laboratory experiments and numerical modelling to inform mitigation strategies and resilience design. We acknowledge this can be resource intensive and in some cases impractical due to hazard and infrastructure complexity, but if the benefit of mitigation strategies is well defined and recognised then such investments become justified. Mitigation for volcanic hazards is also likely to reduce risk for other non-volcanic hazards.

Future research priorities to reduce risk and increase resilience for critical infrastructure sectors we believe should be addressed within the next 10 to 25 years are:

- Focus on quantitative vulnerability estimation for critical infrastructure impacted by volcanic hazards. This should include open source standardised methodologies and databases for collection of quantitative impact data from post-eruption field assessments, laboratory experiments and numerical modelling and the derivation of fragility and vulnerability functions. Developing such approaches for critical infrastructure will be challenging due to the wide variability in system and component design, operational requirements and the interdependency between different infrastructure sectors. However, a standardised approach allows repeatable quantitative vulnerability estimates to be made and facilitates direct comparisons with other critical infrastructure and natural hazards.
- Laboratory analysis of infrastructure systems and components under controlled conditions to more robustly inform vulnerability estimates; particularly for high-value infrastructure components which society requires high levels of reliable performance.
- Increasing the awareness of volcanic hazards, their impacts and the value of volcanic risk management for critical infrastructure operators. This may be achieved through partnerships between volcanic scientists, infrastructure operators and engineers to encourage the inclusion of volcanic hazards in infrastructure site evaluation/assessment criteria, design and contingency planning aimed at increasing resilience.
- Demonstrate the value of volcanic risk management for critical infrastructure by the provision of useful and understandable vulnerability and mitigation information, backed by cost-benefit analysis, to critical infrastructure operators so informed decision making regarding infrastructure operation and resilience can take place.

2.7 Summary

This paper reviews disruption and physical damage impacts to critical infrastructure sectors from tephra falls, pyroclastic density currents (PDC), lava flows and lahars. Data are primarily from post eruption impact assessments and are generally qualitative, although several quantitative assessments are available. Impacts to critical infrastructure can be classified on a continuum from disruption to complete destruction. Impact severity is primarily controlled by the type of hazard, its intensity and the specific type of infrastructure and its design. In general, disruption occurs at low hazard intensities for tephra falls, PDCs and lahars, while physical damage occurs at higher intensities for all hazards. Lava flows are the exception and tend to cause physical damage at all intensities.

Quantitative volcanic hazard assessment is at an advanced state, however, quantitative vulnerability assessments are lacking. The lack of these assessments can be attributed to: (1) difficulties in determining which hazard characteristic is the primary cause of damage to infrastructure and its accurate measurement; (2) ongoing eruptions, clean-up and mitigative strategies can alter infrastructure impacts and are challenging to account for in assessments; and (3) lack of volcanic construction or design codes, or performance guidelines which could prompt and facilitate detailed vulnerability assessment. Despite this, several studies have assessed the vulnerability of buildings and critical infrastructure sectors impacted by tephra fall, PDCs and lahars. To facilitate continued development of vulnerability assessments in volcanology, impacts to critical infrastructure from volcanic hazards should be quantified in a more robust, systematic and standardised manner. We have highlighted a number of aspects to consider when estimating vulnerability and developing fragility and vulnerability functions, such as hazard intensity measures, hazard interactions, infrastructure interdependencies, limitations and uncertainties.

We challenge the volcanology community to create a consistent methodology for the development and refinement of physical vulnerability assessment for all volcanic hazards and critical infrastructure. The final goal is to provide robust quantified vulnerability estimates for volcanic risk managers, decision makers and policy experts in order to minimise disruption, reduce economic losses and loss of life during volcanic eruptions.

2.8 Acknowledgements

We are grateful to Mr. T. Horscroft, Elsevier review paper coordinator, for inviting this review paper. Thanks to Dr. Carol Stewart and Dr. Graham Leonard for discussions and perspectives which improved the content and presentation of this manuscript. We gratefully acknowledge funding support from DEVORA (GW, TW, NID), the Ministry of Business, Innovation and Employment's Natural Hazard Research Platform contract C05X0804 (TW and JC), Mason Trust (GW), Royal Society of New Zealand (Canterbury Branch) travel grant (GW), GNS Science and the Earthquake Commission.

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Chapter Three – Infrastructure impact database and data collection guidelines

3.1 Abstract

Post-eruption impact assessments documenting critical infrastructure impacts are a valuable data source for volcanic vulnerability and risk assessments. While impacts have been documented after historic eruptions, they have not been undertaken in a systematic fashion and resulting data is of variable quantity and quality. In this chapter, I describe the newly developed Critical Infrastructure Volcanic Impacts Database (CIVID), which stores and facilitates the acquisition of post-eruption impact data. The CIVID provides standardised templates for volcano, eruption, hazard, critical infrastructure characterisation and impacts data entry. Post-eruption impact guidelines are presented which follow the database structure and provide standard questions which researchers should aim to answer during volcanic impact assessments. A standardised approach for documenting eruption impacts allows comparison between different eruptions and facilitates the derivation of vulnerability and fragility functions from commonly formatted data. Chapter 4 will demonstrate how the CIVID can be used to derived fragility functions. The database is currently not publicly available and is used for internal research purposes, but it will be made public in due course. The database can be used by researchers to document impacts and in future versions a simplified data entry form will be developed so that infrastructure operators, emergency managers and the public can contribute to eruption impact documentation.

3.2 Introduction

After a volcanic eruption much can be learnt about hazard extent and intensity, societal and critical infrastructure impacts, response and recovery. Knowledge of impacts (defined here as service disruption or physical damage) can help not only in the immediate aftermath with response planning and resource allocation but also over the longer term with future vulnerability assessments. Volcanic vulnerability assessments estimate the physical consequences of volcanic hazards on exposed assets such as critical infrastructure (e.g., electrical supply networks, waste supply and wastewater networks, transportation, communications and associated buildings) and are an essential part of volcanic risk management (see Figure 2.1). Post-eruption impact data are the primary data source used for current volcanic vulnerability assessments as they offer a wealth of information on impact occurrence, mechanisms and management practices. Using post-eruption impact data has the advantage of accounting for a wider range of hazards and exposed asset characteristics than experimental and analytical (numerical) approaches. However, post-eruption assessments are typically site, region, asset, and context specific and therefore knowledge gained may not be transferable to other regions. Nonetheless, by collating impact data from multiple eruptions, regions and assets these limitations may be overcome.

Historically observed post-eruption impacts are documented by many authors (e.g., Blong, 1984; Spence et al., 1996; Blong, 2003; Baxter et al., 2005; Stewart et al., 2006; Wilson et al., 2012; Jenkins et al., 2013; Jenkins et al., 2014) and summarised in Chapter 2. While these studies identify a wide range of impacts to different critical infrastructure and buildings, the vulnerability data are of variable quality and format. In Chapter 2 I identified the need for a standardised approach for the collection and documentation of post-eruption impact data. A consistent approach will: (1) increase data quality and coverage; (2) provide a standard dataset for the derivation of vulnerability and fragility functions, a top priority for volcanic vulnerability assessment (see Chapter 4); (3) facilitate easy comparison between different eruptions and regions; and (4) ensure data is collected and documented in a systematic manner. In this chapter I present a standardised database to document post-eruption impact data and a set of guidelines for the collection of impact data.

This chapter describes: (1) the standardised design template of the Critical Infrastructure Volcanic Impacts Database (CIVID) (Section 3.3); (2) the intended use of the CIVID, development and related difficulties and limitations of its use (Section 3.4); and (3) guidelines and questions for researchers to use when conducting post-eruption impact assessments to obtain consistent data coverage based on the experience of New Zealand Volcanic Impact Study Group (NZ VISG) researchers (Section 3.5). Hazard intensity metric and impact state scale definitions are from Chapter 2, Tables 2.8–2.11 and 2.12–2.15, respectively. Figures 2.4, 2.5, 2.7, 2.9 and 2.13 in Chapter 2, which show infrastructure impacts as a function of hazard intensity, are derived from data in the CIVID. This chapter does not provide a protocol for conducting a full post-eruption impact assessment as there are other situational considerations which need to be arranged, such as human ethics approval, logistics, coordination, local connections, obtaining access, and health and safety regulations. These aspects are likely to vary considerably and establishing a universal protocol is beyond the scope of this chapter.

3.3 Database design

As previously established a standardised approach is required to document post-eruption impact data; a relational database fulfils this requirement. I designed the CIVID to reflect its purpose to document a range of impacts to different critical infrastructure sectors from volcanic eruptions. As such, each infrastructure sector has two tables: one describing site characteristics (e.g., age of infrastructure) and the other cataloguing data regarding volcanic impacts at that site. These infrastructure tables are linked to tables storing data on eruptions and source volcanoes. In addition, there are a number of link and dictionary tables, which respectively maintain the relationships between the main tables and provide lookup functions for common descriptions, e.g., building typology. The CIVID structure is outlined in Figure 3.1 and a detailed structure for buildings is shown in Figure 3.2. The following section is split into sub-sections which describe the different tables and their relationships within the database.

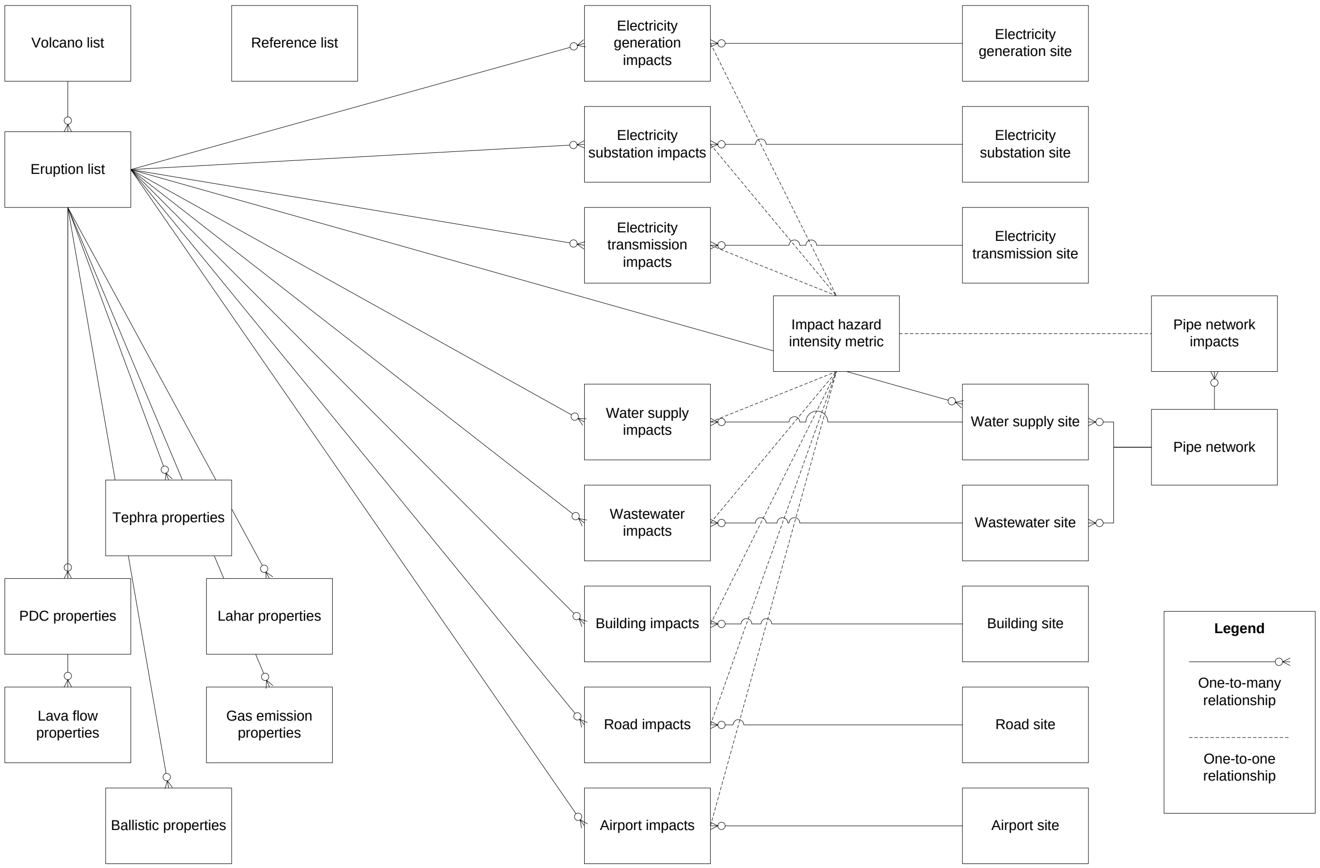

Figure 3.1: Structure of the Critical Infrastructure Volcanic Impacts Database (CIVID). One-to-many relationships (solid lines) relate one record from a table to many records in another table. One-to-one relationships (dashed lines) relate one record from a table to one record in another table. Note; in the database the reference table relates to all other tables; however, to improve diagram readability these relationships are not shown here.

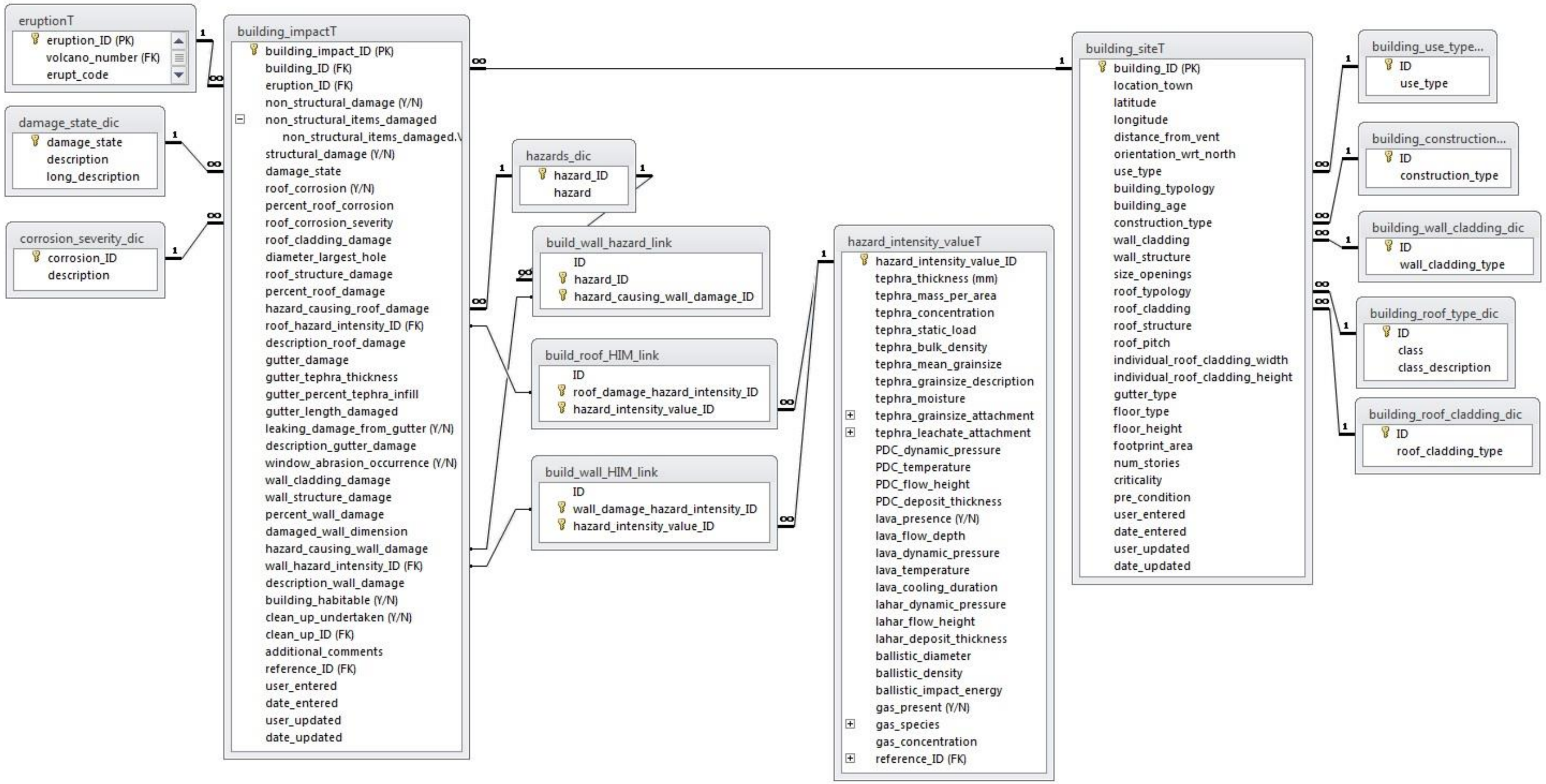

Figure 3.2: Detailed database structure for tables related to building characteristics (building_siteT) and impacts (building_impactsT). Dictionary tables (_dic) act as look-up tables for codes used in other tables. Link tables (_link) allow many-to-many relationships. The '1' and '∞' symbols represent the 'one' and 'many' sides, respectively, of a one-to-many relationship. The reference table is not shown here to improve diagram readability, but is available for every datum.

3.3.1 Volcano and eruption properties

The volcano table contains ~1,500 volcanoes from around the world derived from the Smithsonian Institution's Global Volcano Program (GVP) database (Siebert et al., 2010). The GVP database documents current and known past volcanic activity for all volcanoes active in the last 10,000 years. Two key fields included in this table are the GVP volcano name and volcano number. The volcano number is unique for each volcano and is used to prevent ambiguity regarding volcano name and location for volcanoes that are known by generic or many names (GVP, 2013). Other fields include latitude, longitude, region, sub-region, elevation, primary volcano type and last known eruption. The GVP database is used as it is the international authoritative source for volcanoes and global volcanic activity. In addition, further information about a volcano can be easily obtained from the GVP website (www.volcano.si.edu) using the volcano numbers.

Presently, the eruption table contains 47 eruptions for which there are documented volcanic impacts to critical infrastructure. GVP eruption data is used and supplemented with other literature, typically from local reports, where appropriate and available. Many more eruptions are documented in the GVP database; however, the majority have not impacted infrastructure and/or have no documented impacts and therefore I have not included them in the CIVID. The eruption table is related to the volcano table via the volcano number in a one- (volcano table) to-many (eruption table) relationship. This relationship allows one volcano to have many eruption records but each eruption to only have one volcano record. Data fields in the table include:

- Eruption identification number which uniquely identifies the specific eruption.
- An eruption code comprised of the first three letters of the volcano's name and the last two digits of the eruption year (e.g., PAC10 for Pacaya's 2010 eruption). This is not strictly unique but helps users quickly identify the erupting volcano and year.

- Eruption start and end date or an indication if the eruption is ongoing.
- Eruption size as Volcanic Explosivity Index (VEI) and magnitude where available.
- Average or typical eruption column height.
- Environmental conditions at the time of eruption (e.g., rainfall, wind direction), which can influence impact occurrence and severity.
- Indication of which volcanic hazards were produced during the eruption.

For the purpose of the CIVID, the volcanic hazards included are: tephra falls; pyroclastic density currents (PDC); lava flows; lahars; ballistics and gas emissions. These are the most common volcanic hazards to occur and cause impacts; however, additional hazards (e.g., newly created edifice) can easily be included in future versions of the CIVID. Related to the eruption table are hazard properties tables which record properties of each hazard which occurred during an eruption. These tables include data about hazard extent, volume, duration, composition and particle size. There is also the ability to attach external files into the various tables which, for example, isopach maps, grainsize distributions and tephra leachate results. These hazard property tables are intended to provide an overview and context for the eruption rather than provide hazard property data for specific impacts (see Section 3.3.2).

3.3.2 Critical infrastructure characteristics and impact data

The critical infrastructure sectors currently included in the CIVID are: electrical supply networks, water supply and wastewater networks, transportation (road and air) and associated buildings. Future iterations will also include communication networks and critical components (heating, ventilation and air conditioning and small electrical equipment such as computers) which are common across multiple infrastructure sectors. Due to differences in operation and observed impacts, the electricity supply network is split into three sub-sectors: generation sites; substation sites; and transmission lines. In a similar manner, pipe networks used by the water supply and wastewater networks are considered separately (Figure 3.1) as impacts to pipes occur regardless of the infrastructure sector they belong to.

Each infrastructure sector or sub-sector has two tables; one for general site characteristics and the other for volcanic-induced impacts. The main reason for this separation is because a single infrastructure sector could have multiple impacts during the same eruption, i.e., a one-to-many relationship. For each table there is a required field which indicates whether the data in the table relates to an individual site, an individual section (for pipes and transmission lines), multiple sites or the whole sector. This distinction is made because field data may be collected at these different spatial scales and provision needs to be made to include all data in the database. Also, in publications by the NZ VISG, who commonly undertake post-eruption impact assessments (T.M. Wilson et al., 2014), a section describing general infrastructure characteristics and impacts of a whole sector precedes a more detailed discussion about specific site impacts (e.g., Sword-Daniels et al., 2011; Wardman et al., 2012).

The purpose of the infrastructure site characteristics table is to establish site location, the equipment present and normal operating capacity. Documenting these aspects provides a pre-eruption baseline operating level which can be compared to post-eruption levels to determine impact severity. In addition, reviewing infrastructure site characteristics can highlight certain aspects which may influence vulnerability during future eruptions. The infrastructure site characteristics tables include data fields for the following:

- Unique infrastructure site identification number.
- Infrastructure operating company and/or owner.
- Location (e.g., latitude, longitude, nearby populated centres and distance from the volcanic vent).
- Equipment characteristics (e.g., type of equipment, length, number, materials, equipment location and layout).

- Normal operation of equipment (e.g., people and areas serviced, throughput, production rate and normal water quality levels).
- Preparation for volcanic hazards (e.g., contingency plans, mitigation actions and previous eruption experience).

The infrastructure site characteristics tables are only related to the infrastructure impact tables and not directly to the eruption table (Figure 3.1). This allows infrastructure characteristics to be recorded without being directly related to an eruption, facilitating pre-eruption vulnerability assessment (see Section 3.4.3 for further discussion).

Infrastructure impact tables record any and all volcanic-induced impacts to a specific infrastructure site. Impact tables are directly related to the eruption table in a many-to-one relationship such that one eruption can cause many infrastructure impacts (Figure 3.1). Each infrastructure impact table is also related to its corresponding site characteristics table such that an infrastructure site can have many impacts. In the impact tables, a distinction is made between service disruption and physical damage impacts to provide a simplified classification of the impacts sustained at a particular site.

Two mandatory data fields in the impact tables are the impact state (IS) and hazard intensity metric (HIM) value. The ISs used in the database are from Tables 2.12–2.15 which define four impact states: IS_0 – no damage; IS_1 – cleaning required; IS_2 – repair required; and IS_3 – replacement or financially expensive repair. Recording the IS provides a semi-quantitative assessment of impact intensity at a particular infrastructure site. The HIM value is a measure of hazard intensity which caused a specific impact. For each volcanic hazard many different HIMs can cause impact (see Tables 2.8–2.11) and provision is made in the HIM table to record common HIMs (e.g., tephra thickness, PDC dynamic pressure, lava flow depth, diameter of ballistics) of a particular volcanic hazard at an infrastructure site. If HIM values are not obtained during post-eruption impact assessments, they can be extracted from other data sources such as isopach maps for tephra thickness. Both the HIM value and IS are used in the derivation of vulnerability and fragility functions (Chapter 4): one of the main purposes of the CIVID.

For each infrastructure site, impacts can be recorded by selecting from a pre-populated list. The list is populated with commonly observed impacts from past eruptions (Table 2.5); however, the user can also enter additional impacts if required. This data field is intended to provide quick identification and classification of sustained infrastructure impacts. This classification scheme and recorded HIM values were used to populate impact plots in Figures 2.4, 2.5, 2.7, 2.9 and 2.13. More detailed impact descriptions can be added in the comments section or under specific data fields which are provided for common impacts. For example, for wastewater treatment plants there are specific abrasion, corrosion and filter blockage description data fields. The infrastructure impact tables include data fields for the following:

- Unique infrastructure impact identification number.
- Selection of observed or documented impacts at the site from a pre-populated list.
- Identification of which hazard(s) caused the observed impacts. Currently this list is restricted to tephra falls, PDCs, lava flows, lahars, ballistics and gas emissions.
- Recording the HIM value which caused the impacts (e.g., tephra thickness, PDC dynamic pressure, lava flow depth, diameter of ballistics). This data is recorded in a separate table (Figure 3.1) and is a mandatory data field.
- Assigning an impact state to the infrastructure site to reflect overall impact intensity. This is a mandatory data field.
- Infrastructure-specific data fields which allow more detailed descriptions (e.g., occurrence, severity, how specific impacts were rectified) of common impacts.
- Warnings of eruption or hazard occurrence received by infrastructure operators, as these can influence response, impact occurrence and severity.

- Recording how impacts were managed, whether previous eruption experience aided in current volcanic risk management practices and any potential lessons operators learnt which could be applied in future eruptions.

3.3.3 Data quality and literature references

It is important to know the quality and source of each datum as this allows the user to make an assessment as to the applicability of the data to their needs. Data quality is based on the source of the data (i.e., who collected the data) with the assumption that scientists/researchers obtain higher quality data than infrastructure operators, media or the general public. Table 3.1 defines the data quality indicators used for each record in the CIVID.

Table 3.1: Data quality indicator used in the CIVID based on data source.

Quality indicator	Data source description
0 (lowest)	Public eyewitnesses or media reports
1	Infrastructure operators/managers
2	Qualitative post-eruption impact assessments (scientists)
3 (highest)	Quantitative post-eruption impact assessments (scientists)

Where possible, literature references are provided for each data field in the various tables and are stored in their own references table (Figure 3.1). This approach allows each table to have multiple references for different data fields. In addition, each data field can have multiple references which accounts for multiple authors documenting the same eruption, infrastructure site or impacts. As a minimum, each record in all tables has at least one literature reference which allows users to refer to the original data source for further information.

3.4 Discussion

3.4.1 Intended use of the volcanic impacts database

The CIVID provides extensive documentation of known impacts (i.e., disruption and damage) to critical infrastructure sectors from historic (since 1900 CE, the 79 CE Vesuvius eruption notwithstanding) volcanic eruptions and is the first of its kind. This database will be of interest to volcanic researchers who would normally undertake extensive literature reviews to obtain relevant infrastructure impact and vulnerability data. Database outputs will be of relevance to emergency management agencies and infrastructure operators who will be interested in knowing which infrastructure impacts might be likely to occur and how future volcanic eruptions can be managed.

The database can be used as a research tool to analyse trends in infrastructure impact occurrence, correlate impacts to volcanic hazard intensity values, identify different impact mechanisms and provide data for the derivation of volcanic vulnerability and fragility functions (Chapter 4). In this regard, the CIVID provided data for Figures 2.4, 2.5, 2.7, 2.9 and 2.13 which show common infrastructure impacts as a function of hazard intensity for historic volcanic eruptions. Using these data, impact state scales were derived for all infrastructure sectors for four volcanic hazards (Tables 2.12–2.15). Figure 3.3 shows the frequency of each IS recorded in the CIVID for water supply, wastewater, electrical supply and transportation networks. Data from the database was used to derive the volcanic vulnerability and fragility functions in Chapter 4 which are common quantitative approaches to assess vulnerability and one of the goals of volcanic vulnerability assessment. Using post-eruption impact data to derive these functions has the benefit that impacts that occurred in the past are likely to occur again and the research community can learn from these. As new data are incorporated into the database from future volcanic eruptions or from the re-assessment of past eruptions, volcanic vulnerability and fragility functions can be refined to better predict impacts to infrastructure. Researchers can also use the CIVID to supplement vulnerability data derived from other methods such as laboratory experiments or numerical modelling.

The database also facilitates the systematic collection of post-eruption impact data by providing a standardised format for data entry for each infrastructure sector and volcanic eruption (see Section 3.5 for further discussion).

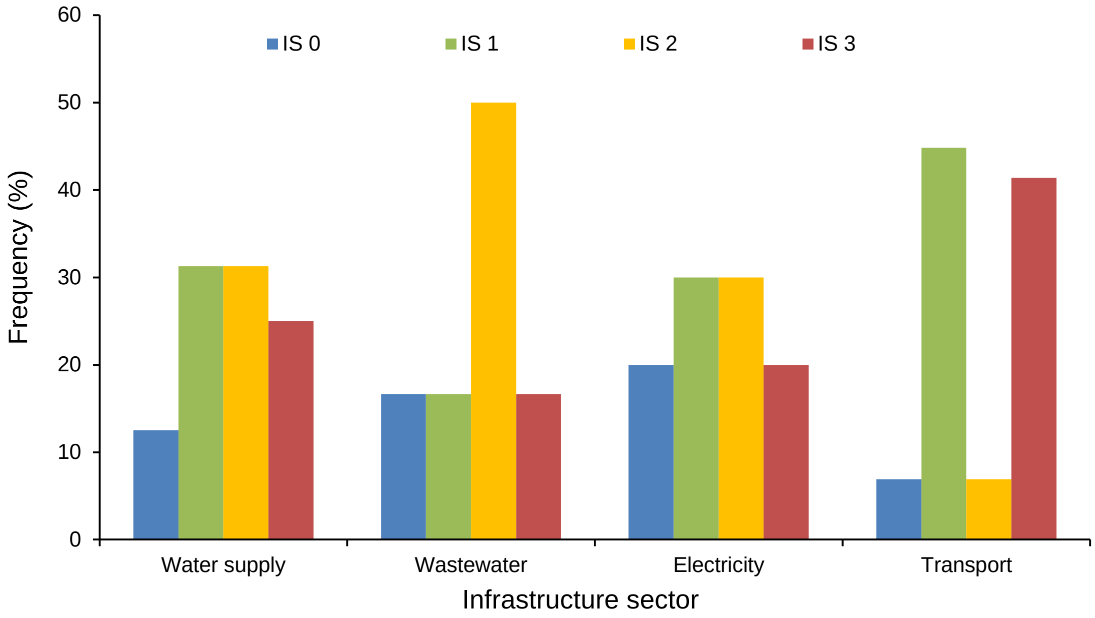

Figure 3.3: Frequency of different impact states (defined in Section 3.3.2) for four infrastructure sectors compiled from post-eruption impact assessments documented in the CIVID. The number of case studies used is: 16 (water supply); 6 (wastewater); 30 (electricity); and 29 (transportation).

3.4.2 Difficulties and limitations

The difficulty in developing this database is obtaining and compiling relevant data. While many eruptions have occurred in the past which have undoubtedly impacted society and infrastructure, there is relatively little documentation of these impacts. In addition, volcanic eruptions which do impact critical infrastructure are infrequent events over human timescales, limiting the quantity of available data (G. Wilson et al., 2014).

In addition, some data may be missed during post-eruption impact assessments because some impacts occur over long time periods (e.g., metal corrosion and abrasion) and the assessment may have occurred prior to these impacts becoming evident. Multiple follow-up impact assessments could overcome this limitation. Tolerance to impacts is likely under-represented as damaged infrastructure is typically the focus of post-eruption impact assessments. The standardised database and data collection guidelines will assist in fully documenting impacts and tolerance in future eruptions, increasing the quantity of impact data.

Currently the CIVID documents observational data obtained from post-eruption impact assessments and does not provide for other data sources such as laboratory experiments, numerical modelling or expert elicitations. These data sets could be included in future versions of the CIVID to provide a complete critical infrastructure vulnerability database, although this would require modification of the existing database structure.

3.4.3 Future developments

Currently the CIVID is not publicly available and is for internal research only, however in the future it is anticipated it will be made public in a web portal that would allow researchers to search and extract infrastructure impact data. In addition, the long term plan is to allow researchers to easily add data to the database. This could be accomplished in a web portal or a phone application where researchers could follow impact data collection guidelines (Section 3.5 and Appendix B) and upload impact data directly into the CIVID after validity checking by the database manager. This approach would allow consistent data to be collected from different volcanic eruptions without relying on one research team (e.g., the NZ VISG) to conduct assessments. Another objective is to develop a modified version of the web portal which could be provided to infrastructure operators or the public in the impacted areas to allow them to document observations in a crowdsourcing type approach.

In the database, additional fields could be added within the critical infrastructure tables to allow researchers to assign vulnerability indicators/scores to different sites. This could then be used to assess the vulnerability of an infrastructure site prior to an eruption, allowing the development of site-specific mitigation strategies. The CIVID would then act as a repository for both pre-eruption vulnerability and post-eruption impact assessment data.

Photographs, either taken by researchers or obtained from other sources, are a valuable resource to assist with impact verification and documentation when back from field, and thus should be collected. The use of aerial or small unmanned aerial vehicles (UAV) could also assist in volcanic impact documentation over large spatial areas or in areas with difficult access. Currently the CIVID does not have a facility to store photographs although this is envisaged in future versions.

3.5 Post-eruption impact assessment guidelines

3.5.1 Motivation

Standardised impact data collection guidelines will enable the consistent and ongoing collection of volcanic impact data and subsequent comparison between volcanic eruptions. The benefit of standardised impact assessments is that the same data are collected for each infrastructure sector, providing consistency within and between eruptions. In addition, multiple researchers or research groups can conduct impact assessments using the same procedure, removing the reliance on a single research group, which could be beneficial during large scale or prolonged volcanic eruptions. Using standardised data collection also allows data to be easily stored in the CIVID.

The post-eruption impact assessment guidelines presented in Tables 3.2 and 3.3 and Appendix B are sets of questions and prompts which can be answered by the investigating researcher or through interviews with local residents, infrastructure operators and emergency personnel. These guidelines are based on the experience of NZ VISG researchers who have systematically documented societal impacts, primarily from tephra fall, for 17 eruptions worldwide (T.M. Wilson et al., 2014). The guidelines follow the general structure of the CIVID such that there are requirements to obtain data regarding the: volcano; eruption; volcanic hazards; critical infrastructure characteristics; and critical infrastructure impacts. As an example these guidelines were used to conduct a post-eruption impact assessment for areas impacted by the 2014 Kelud eruption in Indonesia (Appendix C).

3.5.1.1 Post-eruption impact assessment timing

The timing of a post-eruption impact assessment can determine the quantity and coverage of data obtained. If an impact assessment is conducted soon after an eruption, researchers will be able to directly observe and document any impacts, collecting high quality data. However, immediately after an eruption, emergency response is likely occurring and infrastructure operators and emergency management personnel may be unavailable for interviews. In addition, some impacts, such as metal corrosion and abrasion, may only appear in the future, so the impact assessment will not include it and therefore will not document the full range of impacts.

When an impact assessment is undertaken many months after an eruption, a more complete understanding of the impacts can be obtained, as the majority of the impacts will have occurred. However, at this time researchers may not be able to directly observe any impacts as they may already be repaired, and data will need to be obtained from interviews.

The timing for conducting a post-eruption impact assessment will depend on many factors, for example eruption magnitude, logistics, research permits and funding. The NZ VISG has conducted impact assessments up to ~20 years after eruptions; however, after recent eruptions assessments have been conducted after ~1–9 months (T.M. Wilson et al., 2014).

3.5.1.2 Post-eruption impact assessment scope

The number of sites visited and level of detail of a post-eruption impact assessment depends on a number of factors including hazard extent, personnel, time and funding. Jenkins et al. (2014) suggested different assessment methodologies (e.g., comprehensive, single-point sampling, multi-point sampling, special interest and transect) depending on available resources. With regard to critical infrastructure, the number of sites visited may be low because in a number of cities there are only a few of each infrastructure type. For example, in Auckland, New Zealand, which could be impacted by an eruption from the Auckland Volcanic Field, there are 19 water supply treatment facilities (Watercare, 2015) in comparison with ~470,000 households (Auckland Council, 2014). Resources permitting, as many sites as possible should be visited and at a minimum, location, type of equipment, impact intensity (impact state) and volcanic hazard intensity data should be recorded.

3.5.2 Example case study: electricity supply network

Post-eruption impact assessment guidelines for the electricity supply network are provided here as an example. The questions and data required are divided into: electricity site characteristics (Table 3.2); electricity site impacts (Table 3.3); and HIM value(s) (Table 3.4). Impact assessment guidelines for other infrastructure sectors are provided in Appendix B.

Table 3.2: General site characteristics for all electrical supply infrastructure and specific characteristics for generation sites, substations and the transmission network.

Sub-sector	Assessed item
General	Site identification.
	Name of the site.
	Operating company.
	Town or city site is located within.
	Latitude, longitude, distance from volcano.
	Number of customers served.
	Is the site: one site, a small section or whole network?
	Describe any volcanic hazard contingency or preparedness plans that were in place pre-eruption.
	Describe any contingency plans that have been developed since the eruption.
	Has the site experienced volcanic hazards before and did that experience help this time?
	Have any volcanic-specific mitigation actions been implemented to reduce impacts?
	Age of each site.
	If possible obtain a network or site layout map.
Generation sites	Type of generation used.
	Installed capacity (MW).
	Average annual generation (GWh).
	Number of turbines, type (model) and material.
	List equipment used at the site including control equipment.
	Describe cooling system including number and type of fans.
	Hydroelectric power (HEP) catchment area.
	HEP storage volume.
	Is there a system for high turbidity water to bypass HEP turbines?
	Description of wind turbine and blade design.
	Number, type and inclination angle of solar panels.
	Was station operating at full capacity prior to eruption?
Substation	In which part of the network is the substation located (transmission, distribution, grid exit, grid input)?
	Is the substation located inside or outside?
	Number and voltage of input and output circuits.
	List equipment used at the site including control equipment.
	Number and type of transformers.
	Number and type of circuit breakers.
	Number and type of insulators.

Sub-sector	Assessed item
	Is a gravel ground cover used, if so what is its normal resistivity?
	What safety measures are taken to keep gravel ground cover at a specific resistivity?
Transmission network	Total line length, operating voltages and peak currents of grid and individual line segment assessment relates to.
	What type of conductors are used and are they insulated?
	What type of conductor support structures are used (including dimensions and materials) and number?
	Are pole transformers used, if so what type of transformers?
	What type of insulators are used (including dimensions and materials) and number of sheds and insulator strings? Record for both vertical and horizontal (strain) insulators.
	Are insulators protected from animals or pollutants?
	Does pollution (sea salt, industrial emissions) cause line outages and/or flashovers?
	Are conductors and insulators regularly cleaned to remove contaminants?

Table 3.3: Questions and data required for a post-eruption impact assessment for all electricity supply infrastructure and specific questions for generation sites, substations and the transmission network.

Sub-sector	Assessed item
General	Electricity site identification.
	Eruption identification.
	Was a warning received before the eruption? Who provided the warning? How much warning time was given?
	Describe any steps that were taken to prepare for the eruption.
	Describe how any impacts were managed (shutdown, repair, additional maintenance, clean up).
	Are there any lessons learnt or procedures that would help future eruption response?
Generation sites	Was the generation site tolerant to the eruption and hazard(s)?
	List the impacts observed at the site.
	Were any support buildings impacted?
	What is the impact state (using Tables 2.12–2.15)?
	What hazard caused the impact and what was the HIM value (recorded in Table 3.4)?
	Was electricity generation disrupted, what percentage was generation reduced by and how long was generation disrupted?
	What caused the disruption (hazard itself, cleaning or repair)?
	Did HEP turbines suffer from abrasion, if so how much tephra passed through them, when did abrasion occur, how severe was the abrasion, how was abrasion repaired?

Sub-sector	Assessed item
	Did cooling systems suffer abrasion, if so when did abrasion occur, how severe was the abrasion, how was abrasion repaired?
Substation	Was the substation site tolerant to the eruption and hazard(s)?
	List the impacts observed at the site.
	Were any support buildings impacted?
	What is the impact state (using Tables 2.12–2.15)?
	What hazard caused the impact and what was the HIM value (recorded in Table 3.4)?
	Describe any impacts to transformers and methods to restore their function.
	Was there any disruption to transmission, switching or control operations at the substation, if so how long did the disruption last?
	Did the gravel ground cover have to be cleaned, if so, why was it cleaned (safety, low resistivity), how was it cleaned and how long did it take?
Transmission network	Was the distribution and transmission network tolerant to the eruption and hazard(s)?
	List the impacts observed.
	What is the impact state (using Tables 2.12–2.15)?
	What hazard caused the impact and what was the HIM value (recorded in Table 3.4)?
	Did insulator flashovers occur, if so, how many insulators suffered flashover and what type of insulators were they? Was flashover one-off or continuous?
	Was electricity transmission disrupted, if so, for how long? How were circuits reconnected (automatically or manually)?
	Was there any tephra on the underside of insulators which suffered flashover?
	Were flashovers influenced by weather/rain?

Table 3.4: Hazard intensity metrics table. For each impacted infrastructure site at least one hazard intensity metric must be recorded for the hazard that caused impact(s).

Hazard	Hazard intensity metric (HIM)
Tephra fall	Thickness (mm)
	Mass per unit area (kg/m^2)
	Static load (kPa)
	Atmospheric concentration (mg/m^3)
	Mean grainsize (mm)
	Qualitative description of grainsize
	Moisture content (dry, moist, wet, saturated)
PDC	Dynamic pressure (kPa)
	Temperature (°C)
	Emplacement flow height (m)
	Deposit height (m)

Hazard	Hazard intensity metric (HIM)
Lava flow	Lava present (yes/no)
	Depth of flow (m)
	Dynamic pressure (kPa)
	Temperature (°C)
	Cooling time (hours)
Lahar	Dynamic pressure (kPa)
	Emplacement flow height (m)
	Deposit height (m)
Ballistics	Diameter (mm)
	Particle density (kg/m^3)
	Impact energy (J)
Gas emission	Gas present (yes/no)
	Species (CO_2, SO_2, H_2S, HCl, HF)
	Concentration (ppm)

3.6 Summary

The CIVID currently contains 47 historic volcanic eruptions which have impacted critical infrastructure sectors. Data are sourced from post-eruption impact assessments, the primary data source for volcanic vulnerability research, and stored in the database using standard templates. Standardising volcanic impact data allows easy comparison between different eruptions, quick identification of missing data and facilitates the derivation of volcanic vulnerability and fragility functions. The CIVID provides relational data tables for source volcanos, eruptions, hazard occurrence and intensity, infrastructure characteristics and impacts. Standardised post-eruption impact assessment guidelines and questions, based on the experience of NZ VISG researchers, specify the required data for each database table.

This database is the first of its kind for volcanic hazard impacts to critical infrastructure and will provide a useful resource for volcanic vulnerability and risk researchers once made publicly available. The goal of the CIVID is to facilitate the ongoing documentation of infrastructure impacts in a consistent way and provide vulnerability data for the derivation of volcanic vulnerability and fragility functions. The CIVID can help researchers assess volcanic risk and develop appropriate risk reduction solutions; the goal of both the Global Volcano Model (GVM; www.globalvolcanomodel.org) and the United Nations Global Assessment of Risk 2015 (UNISDR, 2015).

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Chapter Four – Framework for developing volcanic fragility and vulnerability functions

4.1 Abstract

Assessment of volcanic risk using sophisticated probabilistic models is increasingly desirable for risk management, particularly for loss forecasting, critical infrastructure management, land-use planning and evacuation planning. This has driven the development of sophisticated probabilistic hazard models over the past decades; however, volcanic vulnerability models of equivalent sophistication have lagged considerably behind. Therefore, there is an increasingly urgent requirement for development of quantitative vulnerability models, such as vulnerability and fragility functions which provide quantitative relationships between volcanic impact (damage and disruption) and hazard intensity. Few such functions are presently available, except for tephra fall impacts to buildings, which have been driven by life safety concerns.

The aim of this chapter is to present a structured approach for the quantitative assessment of infrastructure vulnerability to volcanic hazards. The framework I present here focuses on the derivation of vulnerability and fragility functions for critical infrastructure impacted by volcanic hazards. The framework details impact data sources, different impact intensity scales, preparation and fitting of data, uncertainty analysis and documentation. The primary data sources are post-eruption impact assessments, supplemented by laboratory experiments and expert judgment, with the latter drawing upon a wealth of qualitative studies. A number of different data processing and function fitting techniques can be used to derive functions; however, due to the small datasets currently available, simplified approaches are discussed. The most important aspect of function derivation is the documentation of data processing, assumptions and limitations. Documentation provides transparency of the process used and allows others

to update functions more easily. Using a standardised approach, a volcanic risk scientist can step though the process and requirements to derive a fragility or vulnerability function, which can be easily compared to other functions and updated when new data become available. Using the methodologies in this chapter, I derive fragility and vulnerability functions for discrete tephra fall impacts to the electricity supply, water supply, wastewater and transport networks. Functions present the probability of an infrastructure site being equal to or exceeding one of four impact states as a function of tephra thickness. These functions represent the first attempt at quantifying the vulnerability of critical infrastructure sectors to tephra fall using fragility and vulnerability functions.

4.2 Introduction

Volcanic eruptions are multi-hazard events which pose considerable threat to society, including critical infrastructure (Cottrell, 2014; G. Wilson et al., 2014). Critical infrastructure such as electrical supply networks, water and wastewater networks, transportation, communications and associated buildings, are man-made systems and processes which function together to deliver essential services to society (Rinaldi et al., 2001). To reduce impacts and loss of critical infrastructure during volcanic eruptions, successful risk assessment and management is required. This requires the combination of hazard, exposure and vulnerability assessments (Figure 2.1). Sophisticated quantitative probabilistic volcanic risk models are increasingly desirable for volcanic risk management, particularly for loss forecasting, infrastructure management and land-use planning. This has driven the development of sophisticated probabilistic hazard models (e.g., Schilling, 1998; Bonadonna, 2006; Costa et al., 2006; Del Negro et al., 2008; Wadge, 2009). However, vulnerability models have lagged considerably and there is an increasingly urgent need for quantitative vulnerability assessment of volcanic hazard impacts. Quantitative vulnerability assessments are available for buildings (e.g., Spence et al., 2005; Zuccaro et al., 2008; Jenkins and Spence, 2009), which have been primarily driven by life safety concerns for the occupants. For critical infrastructure there are a number of qualitative assessments (e.g., Patterson, 1987; Johnston and Nairn, 1993; Daly and Wilkie, 1999; T.M. Wilson et al. 2012; Jenkins et al., 2014b; G. Wilson et al., 2014) however, quantitative vulnerability assessments are lacking and those available are derived using different methods. To address the need for comprehensive quantitative volcanic vulnerability assessments for all infrastructure sectors, a framework is required which guides volcanic risk scientists through the process of conducting quantitative volcanic vulnerability assessments.

The focus of this chapter is the quantification of critical infrastructure vulnerability to volcanic hazards. The primary aim of vulnerability assessments is to derive a relationship between hazard intensity (e.g., tephra thickness, flow dynamic pressure) and damage, disruption or other impact metric to infrastructure components or sectors. There are a number of approaches, both qualitative and quantitative, to assess vulnerability of exposed elements to volcanic hazards, these are reviewed in Section 4.3.1. A brief review of the currently published vulnerability and fragility functions for vulnerability assessment in volcanology is presented in Section 4.3.2, with additional material in Appendix A. Developing fragility and vulnerability functions for critical infrastructure sectors impacted by volcanic hazards requires a standard framework. The framework presented in Section 4.4 outlines a methodology for the derivation of vulnerability and fragility functions, focusing on input data (Section 4.4.1), impact and hazard intensity metrics (Sections 4.4.2–4.4.3), function fitting (Section 4.4.4), uncertainties analysis (Section 4.4.5) and documentation (Section 4.4.6). The framework is designed to be a living document that can and should be updated with new approaches for developing functions when they become available. A suite of fragility and vulnerability functions for four critical infrastructure sectors impacted by volcanic tephra fall is presented in Section 4.5. These functions are a first attempt at quantifying vulnerability of critical infrastructure sectors for tephra fall impacts and should be updated (e.g., calibration, adjust function fitting, improve uncertainty assessment) when new volcanic impact data becomes available.

4.3 Volcanic vulnerability assessment

4.3.1 Volcanic vulnerability assessment approaches

There are a number of qualitative and quantitative approaches that can be used to assess vulnerability of exposed elements to volcanic hazards (Table 4.1). Use of relatively simple qualitative descriptions of volcanic hazard impacts to different exposed elements has formed an important foundation of volcanic impact knowledge. This knowledge has been successfully used for volcanic risk management, such as informing of emergency management exercises, development of public and sector specific information resources and some risk assessments (T.M. Wilson et al., 2014). A formative review on the subject is presented by Blong (1984), who documented impacts to society, infrastructure and agriculture from historic eruptions. Since this review, various authors (e.g., Spence et al., 1996; Blong, 2003a; Baxter et al., 2005; Stewart et al., 2006; T.M. Wilson et al., 2012; Jenkins et al., 2013; Jenkins et al., 2014a; G. Wilson et al., 2014) have updated the knowledge base with examples from recent eruptions. These works have contributed to a broader and deeper understanding of the impacts that are likely to occur to infrastructure sectors during an eruption. This information allows the identification of vulnerable infrastructure components and knowledge gaps where directed research could be undertaken to increase our understanding. This approach also allows simplified information about likely impacts to be presented to infrastructure operators (e.g., T.M. Wilson et al., 2014) such that they can develop their own risk mitigation strategies.

Building upon qualitative descriptions of likely impacts, vulnerability indicators are used to represent an infrastructure property or system which influences vulnerability or resilience to natural hazard impacts. For example, a vulnerability indicator for water supply is the water source. If water is sourced from open water bodies the system is likely to have higher vulnerability to tephra fall as tephra can easily enter the water body compared to a groundwater source which is protected (C. Stewart, pers. comm., 2015). These indicators can be expressed either with qualitative descriptors or numerical values. Indicators allow relative comparison between different spatial areas that have been assessed with the same set of indicators (Birkmann, 2007).

While qualitative descriptions of impacts provide useful information, a move towards quantification is required to facilitate more robust numerical calculations of risk, allowing comparisons between infrastructure sites and other natural hazard risks (T.M. Wilson et al., 2012; Jenkins et al., 2014b; G. Wilson et al., 2014; Brown et al., 2015). In the first instance this can be achieved by categorising or ordering volcanic vulnerability data based on impact intensity. Impact state (IS) scales and threshold levels are commonly used to categorise data (Blong, 2003b). These approaches (ISs and threshold levels) are very similar in that they both categorise vulnerability data into discrete states (Table 4.1), which can be used to compare volcanic impacts between different locations. These scales can also be used after an eruption to back-calculate hazard intensity given the observation of a particular IS (e.g., Jenkins et al., 2013). For example, if a building is observed to be at a particular IS after an eruption, then a particular thickness of tephra is likely to have fallen at that site, depending on building typology and tephra density, to cause the observed damage.

The most complex and advanced vulnerability approach is the use of fragility and vulnerability functions. Two types of vulnerability functions are defined here as those correlating hazard intensity to a component's damage or function loss as: (1) an index or a percentage relative to total impact (e.g., 90% damaged); or (2) an economic cost which is either an absolute cost of repair and/or replacement or a ratio of cost of repair to cost to replace (i.e., damage ratio) (Tarbotton et al., 2015). A fragility function is defined as the probability that a particular impact state will be reached or exceeded for a given hazard intensity (Rossetto et al., 2013; Tarbotton et al., 2015). It follows that vulnerability functions describe mean impact levels of a component or infrastructure sector, while fragility functions describe a range of possible impact outcomes and their associated probability of occurrence (Tarbotton et al., 2015). Whether vulnerability or fragility functions are developed is dependent on the specifications of the vulnerability assessment and available volcanic impact data. Functions are normally developed for use within risk assessments and for loss estimation. In this context the functions provide the vital calculation link between hazard intensity and damage (loss) upon which risk mitigation and management decisions are based. Functions can also be developed which consider mitigation actions, such as strengthening of components or clean-up, providing useful data for risk reduction cost-benefit analyses.

4.3.2 Existing volcanic vulnerability and fragility functions

In volcanology there are fewer existing vulnerability and fragility functions than other natural hazard fields (e.g., earthquake). There are a number of reasons for this: (1) volcanic hazards are not often considered in infrastructure hazard assessments; (2) volcanic hazards are rarely considered in catastrophe modelling; (3) there are no building or infrastructure design codes for volcanic impacts which would prompt the derivation of functions; and (4) volcanic eruptions are infrequent events on human and infrastructure timeframes (Douglas, 2007; G. Wilson et al., 2014). In addition, a range of intrinsic volcanic hazard properties can cause different impacts, leading to difficulties in deriving functions (see Section 4.4.3). Despite these challenges, several vulnerability and fragility functions have been developed for volcanic hazards (see Table 2.4) and are briefly reviewed below. See Appendix A for a detailed review.

Table 4.1: Description, advantages and disadvantages of different vulnerability assessment approaches for volcanic hazards in order of increasing complexity, data requirements and quantification. Selected examples are provided for each approach.

Name	Description	Advantages	Disadvantages	Example
Qualitative descriptions	Qualitative description of probable impacts to infrastructure based upon the presence of a volcanic hazard.	Can provide detailed explanation of likely impacts and vulnerabilities for each infrastructure sector, highlighting where mitigation strategies could be implemented.	May not provide an indication of the differing levels of vulnerability at a particular site and difficult to compare to other sites. No spatial extent of vulnerability or impacts is required.	T.M. Wilson et al. (2012) and G. Wilson et al. (2014) review and document impacts to critical infrastructure from historic eruptions.
Vulnerability indicators	Vulnerability indicators are an attribute or property of a system which influences vulnerability or resilience to volcanic hazards. The degree to which this attribute influences vulnerability can be expressed qualitatively (e.g., high, medium, low) or with numerical values that can be summed to provide an overall vulnerability value/score.	Identifies which attributes or properties influence vulnerability and/or resilience, providing a basis for further research. Can quickly and easily provide relative spatial distribution of areas of different vulnerability.	Assigning qualitative descriptions or numerical values to indicators can be subjective. Can be difficult to have common indicators and rankings for different spatial scales and different infrastructure designs.	Galderisi et al. (2012) used infrastructure vulnerability indicators to assess vulnerability of volcanic hazards on Vulcano Island, Italy.

Name	Description	Advantages	Disadvantages	Example
Impact states (IS)	Impact state scales categorise infrastructure damage or disruption into a set number of defined states, typically ranging from no damage to complete destruction. Each state is typically assigned a numerical vulnerability value such as repair cost, damage ratio (repair cost relative to replacement cost) or percentage of damage.	Allows simple classification of impact into a number of states. Provides distribution of impact states and comparison between impacted areas. Easy to characterise post-eruption.	Assignment of impact states to impacted areas is subjective and relies on expert judgment. Qualitative impact descriptions may not cover all aspects of impact or infrastructure design.	Spence et al. (1996) developed a damage scale for the classification of tephra induced building damage following the 1991 Mt. Pinatubo eruption.
Threshold levels	Similar to damage states in that impacts are categorised into a set number of states; however, in addition to the vulnerability values, each impact state is also assigned hazard intensity threshold values (e.g., tephra thickness, dynamic pressure).	Provides a relationship between impact state (i.e., damage and disruption) and hazard intensity. Providing a range of hazard intensity threshold values accounts for some uncertainty within vulnerability estimates.	The selected hazard intensity metric may not be appropriate to estimate impacts for all infrastructure components. The wide range of infrastructure design and operation characteristics influences vulnerability.	Spence et al. (2004), Jenkins et al. (2014b) and G. Wilson et al. (2014) have developed threshold level scales which indicate hazard intensity for each damage state for buildings and critical infrastructure.
Fragility and vulnerability functions	Quantitative functions (i.e., mathematical equations). Vulnerability functions express relative loss or economic cost to hazard intensity. Fragility functions express the	Impact intensity relationship is continuous over a range of hazard intensities and is not bounded by thresholds. Ability to have multiple functions for different	Requires large statistically valid datasets for robust correlations. The selected hazard intensity metric may not be appropriate to estimate	Spence et al. (2005), Zuccaro et al. (2008) and Wardman (2013) have developed fragility functions for tephra fall impacts on buildings

Name	Description	Advantages	Disadvantages	Example
	probability of a level of impact being equaled or exceeded for a given hazard intensity.	infrastructure components and typologies if data are available. Mathematical approach can account for some of the uncertainty associated with these assessments. Feed into quantitative risk assessments for impact and loss estimation.	impact for all infrastructure components. Functions are only applicable to the infrastructure typology they were derived for and may not be widely used without modification.	and electrical transmission systems.

The majority of the published functions have been derived for tephra fall (Spence et al., 2005; Kaye, 2007; Jenkins and Spence, 2009; Maqsood et al., 2014), PDC (Spence et al., 2007; Zuccaro et al., 2008; Jenkins and Spence, 2009) and lahar (Zuccaro and De Gregorio, 2013) induced building damage. The development of these functions is primarily driven by life safety aspects for occupants during volcanic eruptions. These functions have been derived using data from numerical failure calculations, mechanical experiments, post-eruption impact assessments and expert judgment. The majority of the tephra fall fragility functions are derived specifically for Neapolitan (Italy) buildings because of the large population living close to or on the flanks of Mt. Vesuvius, one of the most dangerous volcanoes in the world (Baxter et al., 2008). For accurate vulnerability assessment these functions will have to be modified or new fragility functions will need to be developed for roof typologies in other parts of the world. Functions derived by Maqsood et al. (2014) are based on global building typologies and therefore have wider applicability.

Few vulnerability or fragility functions exist for volcanic impacts to critical infrastructure. Published functions are available for tephra fall impacts to electrical transmission networks (Wardman, 2013), wastewater networks (Kaye, 2007), transportation networks (Kaye, 2007) and laptop computers (G. Wilson et al., 2012) (Table 2.4). Vulnerability estimates, based on volcanic hazard intensity thresholds, are also available for the majority of infrastructure sectors and volcanic hazards (Chapter 2; Spence et al., 2004; Jenkins et al., 2014b). Due to the lack of quantitative post-eruption impact data, these infrastructure functions have been derived through laboratory experiments and qualitative expert judgment.

The review of critical infrastructure impacts from volcanic hazards (Chapter 2) and available volcanic vulnerability and fragility functions has several key findings:

- A number of vulnerability and fragility functions are available for buildings and agriculture, although mostly for tephra fall impacts.

- There have been few, if any, attempts at developing volcanic vulnerability and fragility functions for critical infrastructure sectors. This is primarily due to difficulties assessing vulnerability across a wide range of infrastructure typologies, designs, operating practices and societal pressures.
- The majority of available volcanic vulnerability and fragility functions are derived for specific infrastructure and building typologies. While this increases their applicability and accuracy for local risk assessments, these functions cannot be used in other areas. For regional or global volcanic risk and vulnerability assessments, derived functions will need to account for a range of infrastructure typologies or assume generic typologies.
- There are limited quantitative empirical (post-eruption impact assessments and laboratory experiments), analytical or theoretical data which can inform the development of volcanic fragility or vulnerability functions for critical infrastructure sectors.
- There are a large amount of qualitative vulnerability data available, primarily from post-eruption assessments, which can be used to inform quantitative volcanic vulnerability assessments. However, a methodology is required to bring both qualitative and quantitative data together to develop quantitative vulnerability estimates for critical infrastructure sectors. Hence the need for the volcanic vulnerability framework developed in Section 4.4, which provides a method to use all vulnerability data to derive vulnerability and fragility functions.

4.4 Volcanic vulnerability and fragility framework

To assess the vulnerability of critical infrastructure to volcanic hazards in a robust and systematic way, a framework is required which guides volcanic risk scientists to derive vulnerability estimates. This method focuses on fragility and vulnerability functions as quantitative approaches to assess vulnerability of critical infrastructure to volcanic hazards. The definitions for these functions are:

- Vulnerability functions – a component's damage or function loss as a value relative to total impact or as an economic cost as a function of hazard intensity.
- Fragility functions – the probability that a particular impact state will be equalled or exceeded as a function of hazard intensity.

Figure 4.1 shows a framework for the derivation of volcanic vulnerability and fragility functions. This section is structured to follow that of the framework. The framework presented here is based upon similar frameworks used for earthquake (e.g., Rossetto et al., 2014a) and tsunami (e.g., Tarbotton et al., 2015) vulnerability assessments.

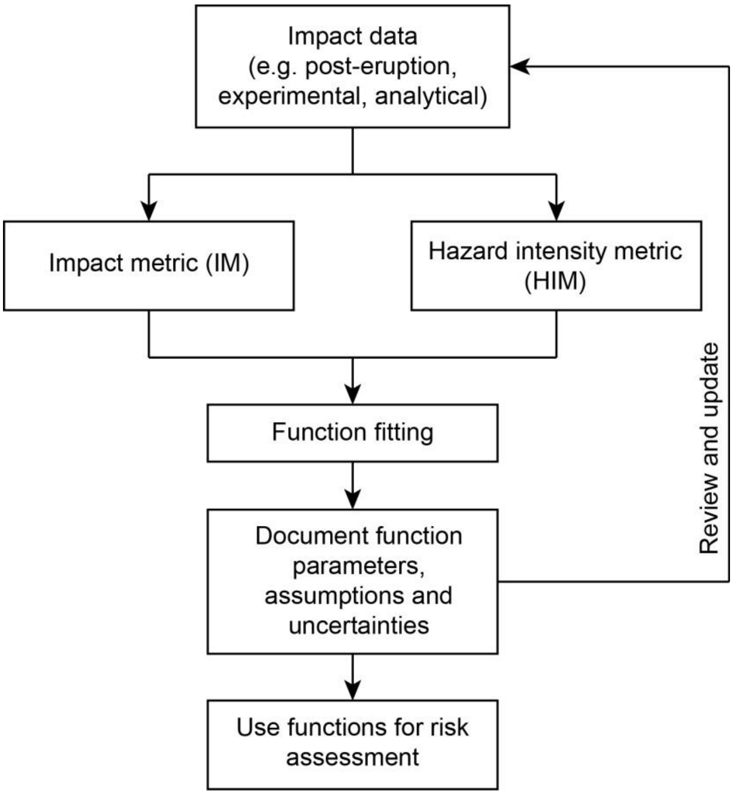


Figure 4.1: Empirical framework for deriving vulnerability and fragility functions for critical infrastructure sectors impacted by volcanic hazards.

4.4.1 Impact data

The data which are used to derive vulnerability and fragility functions is henceforth termed as impact data. Impact data relates infrastructure impact to hazard intensity and can be classified into four main groups: empirical; expert judgment; analytical; and hybrid (Schultz et al., 2010). Each of these data groups are summarised in Table 2.3 and discussed in more detail in this section.

4.4.1.1 Empirical data

Empirical data are observations of critical infrastructure impacts at different hazard intensities sourced from previous volcanic eruptions (post-eruption impact data) or from controlled laboratory experimentation. The main assumption of post-eruption impact data is that past impacts will likely occur again in the future (Rossetto et al., 2014a). Post-eruption impact data are highly specific to hazard conditions which caused the observed impacts and differences in hazard conditions will likely result in different impact outcomes. The typology of impacted assets will influence impact occurrence; therefore impact data might not be applicable to other infrastructure typologies. To minimise these variations, a large dataset, which takes into account a wide range of hazard conditions and asset typology, is required. Therefore, when obtaining or using post-eruption impact data, it is important to understand and document infrastructure typology and the volcanic hazard conditions which lead to the observed impacts. Multiple volcanic hazard occurrences, i.e., prolonged eruptions or tephra remobilisation, can influence impact occurrence, as impacts will be aggregated from multiple eruptions (Rossetto and Elnashai, 2003). Refer to Chapter 3 and Appendix B for standardised guidelines for obtaining and documenting post-eruption impact data.

Laboratory experiments allow for the systematic calculation of volcanic vulnerability of a certain infrastructure component(s) at specific hazard intensities. Laboratory experiments can provide control for most variables, allowing the examination of specific impact mechanisms. Figure 4.2 outlines a generic methodology to undertake experiments with critical infrastructure for tephra fall impacts. The methodology will differ for each experiment depending on purpose of the experiment and the infrastructure system being examined. Not every infrastructure component or sub-sector can be examined experimentally for three main reasons: (1) cost of experimental setup; (2) component(s) too large to fit in laboratory; and (3) removing an individual component from a system could change its performance and vulnerability characteristics. The selection of which component or sub-sector to experiment with is generally determined by previous knowledge of its vulnerability to volcanic hazards, while also accounting for the considerations above. Laboratory experiments should be repeated to account for experimental variability and allow for uncertainty characterisation.

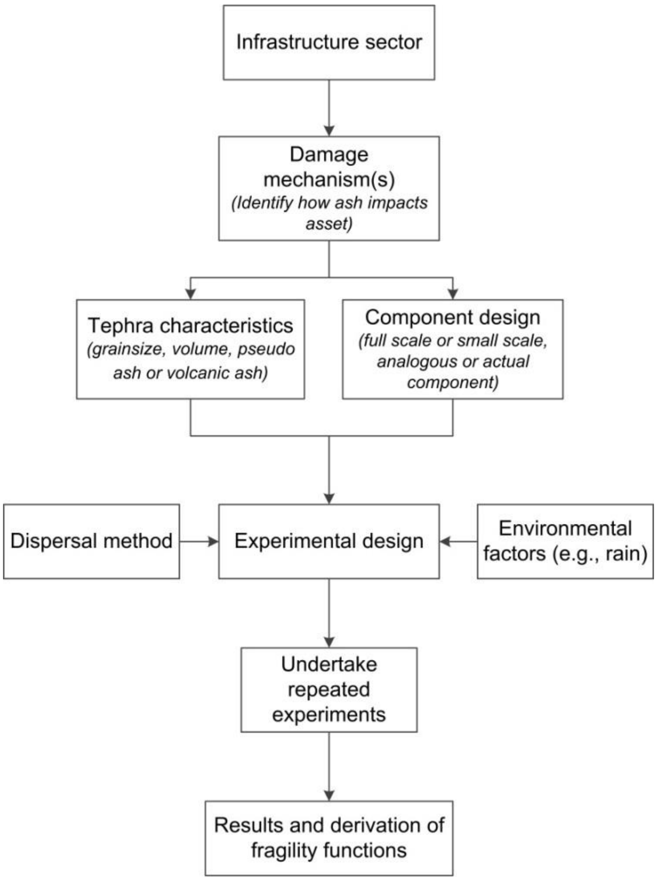


Figure 4.2: Flowchart outlining the general methodology for conducting laboratory experiments to determine infrastructure component vulnerability from tephra fall impacts.

4.4.1.2 Expert judgment data

Expert judgment can be used to estimate vulnerability and fragility when other data (e.g., empirical, analytical) are unavailable (Rossetto et al., 2014a). Expert judgment can also be used to refine or update existing functions which may have been derived from other data sources. A benefit of using experts is that they are able to consider a range of volcanic hazard conditions and infrastructure elements when assessing vulnerability. The selection of experts is important, as not all experts are equally knowledgeable in volcanic hazards, infrastructure and their vulnerabilities or skilled at making scientific judgments (Aspinall and Cooke, 2013). It is also important that experts are familiar with the expert elicitation process and what the goals of specific elicitations are. As such, facilitators need to provide detailed information before any discussions, which outline the objectives, definitions, project context and how the process will be conducted.

There are numerous expert elicitation methods (Aspinall and Cooke, 2013) including the Delphi process and Cooke's Classical Model (Jaiswal et al., 2011), the two most common methods. In the Delphi process each expert provides an answer for the posed question in isolation. Then experts view each other's answers anonymously and are allowed to revise their original answer. This process is repeated until a single acceptable (consensus) answer is obtained (Dalkey, 1969). For Cooke's method, answers provided by experts are weighted by their performance based upon their answers of various seed questions (Jaiswal et al., 2011). Seed questions are questions in which the facilitator knows the exact numerical answers, but experts do not, but are able to provide credible answers.

To use these methods to develop vulnerability and fragility functions, the facilitator elicits values of vulnerability and fragility for a particular asset at various defined hazard intensities. One approach is to have experts provide select values at 50% (mean) and one of more quantile values (e.g., 5th and 95% percentiles) (Jaiswal et al., 2011) rather than defining a complete distribution. Asking experts to provide estimates on quantile values captures their uncertainty about the vulnerability. Values provided by the experts are then weighted by their performance score (in Cooke's method) and a geometric mean is taken and a vulnerability or fragility function is derived. Expert values can also be given equal weightings, and compared to those with un-equal weightings. To derive vulnerability functions for tephra fall induced building damage, Maqsood et al. (2014) instructed experts to derive functions in isolation prior to discussing functions in a group environment. The individual expert functions were presented alongside weighted average functions.

4.4.1.3 Analytical data

Analytical approaches use numerical models to calculate vulnerability at different hazard intensities. This approach is predicated on the development of an appropriate and applicable model that accurately represents the infrastructure system and its vulnerability (Rossetto and Elnashai, 2003). Models and their results should be verified against post-eruption impact data and/or experimental results (Maqsood et al., 2014). This method has been used to determine vulnerability of buildings subject to tephra fall (e.g., Spence et al., 2005) and PDCs (e.g., Spence et al., 2004; Zuccaro et al., 2008). Analytical approaches have not been used to assess the vulnerability of critical infrastructure to volcanic hazards. Using numerical models for critical infrastructure requires an advanced understanding (greater than currently available) of vulnerability to define appropriate models.

4.4.1.4 Hybrid data

Volcanic vulnerability and fragility functions can be derived by using a combination of empirical, expert judgment and analytical data to overcome their individual limitations. There are many ways to implement hybrid approaches, such as:

- Develop functions with analytical data and validate with empirical data.

- Develop functions with expert elicitation methods using empirical data as a guide and for validation.
- Derive different segments of the same function using different data sets to overcome limited vulnerability data (Schultz et al., 2010).

4.4.1.5 Combining datasets

Different datasets may need to be combined such that sufficient data are available to derive vulnerability and/or fragility functions. However, care must be taken when combining datasets, as there will be different biases, sources and magnitudes of uncertainty (Calvi et al., 2006) which can influence the quality of the resulting function(s).

In the case of post-eruption impact assessment data, there may be many different datasets available for different eruptions and locations, all of which could have variable detail and quality. Prior to combining, Rossetto et al. (2014b) suggests impact data should be harmonised by: (1) assuring data type are the same form, e.g., if one dataset is at building-by-building scale and another contains grouped data (e.g., multiple buildings in one area), the more detailed data should be aggregated to the grouped scale; (2) assuring building and infrastructure typology is consistent among datasets, if not, the most general typologies should be used; and (3) assuring the impact scales are identical across datasets, if not, a conversion to the coarsest scale (i.e., the scale with the least levels) should be undertaken. Providing consistency among the different datasets allows easier derivation of vulnerability and fragility functions. Infrastructure impact scales for four volcanic hazards are developed in Chapter 2 and should be used as the common impact scales for future post-eruption impact assessments. In Chapter 3 and Appendix B standardised post-eruption impact assessment guidelines are presented for each infrastructure sector to provide consistency for impact data collection.

4.4.1.6 Data quality rating

Each impact dataset will have differences in data quality dependent on how data were obtained. Here, a qualitative quality rating system is used to indicate the quality of data for different infrastructure components and sectors (Table 4.2). Where possible, high quality data should be preferentially used to derive volcanic vulnerability and fragility functions. These quality ratings also highlight which sectors need further research to categorise their volcanic vulnerability.

Table 4.2: Data quality ratings and descriptions used to rate the quality of volcanic vulnerability data for each infrastructure sector and sub-sector.

Quality rating	Data quality description
A (highest)	Volcanic impacts documented post-eruption from multiple locations (large datasets) and statistically valid analytical modelling or experiments have been undertaken at multiple hazard intensities.
B	Volcanic impacts have been observed post-eruption with recorded hazard intensity and experimental studies or analytical calculations have been undertaken.
C	Volcanic impacts have been observed by scientists or infrastructure operators post-eruption and hazard intensity level is recorded.
D	Volcanic impacts have been observed and reported post-eruption by eye-witnesses (public, media and infrastructure operators).
E (lowest)	Volcanic impacts are possible, but have not yet been observed or identified.

4.4.2 Impact metrics (IM)

An impact metric (IM) is used to assess volcanic impact intensity for a particular infrastructure component or sector. Impact metrics are commonly bounded between 0–1 or 0–100 and are the dependent variable of vulnerability and fragility functions. For vulnerability functions, the IM can be a value or index which describes impact or economic loss. Any IM can be used for a vulnerability function with appropriate justification for its use. Common IMs for vulnerability functions are:

- Damage percentage – percentage of damage sustained by an asset compared to pre-impact condition (e.g., 90% damaged).

- Loss of function – loss of function of an asset as a percentage compared to pre-impact condition (e.g., a water treatment plant is 80% functional).
- Damage index – damage percentage normalised between 0–1.
- Function loss index – loss of function percentage normalised between 0–1.
- Damage ratio – a ratio between the cost of repair relative to cost of replacement.
- Economic cost – absolute cost of impact(s) in dollar amounts.
- Impact state (IS) – states of damage and disruption defined by qualitative impact descriptions (see Section 2.5.3.2 for impact state descriptions for volcanic hazards).

The IM for fragility functions is the probability of an asset being equal to or exceeding a specified level of impact. Typically the level of impact is defined by ISs. The fragility function gives the probability of being equal to or exceeding IS_i. Commonly fragility functions are derived for each IS (i.e., a set of fragility functions) or only for the highest IS. Given that ISs are sequential, such that IS_i implies that IS_{i-1} has occurred, then the probability of being equal to a specific IS can be calculated by the difference between consecutive ISs.

4.4.3 Hazard intensity metrics (HIM)

A hazard intensity metric (HIM) describes the intensity of a volcanic hazard at a particular site and is the independent variable of vulnerability and fragility functions. Volcanic hazards have a number of different properties which can convey intensity. Different properties lead to different mechanisms of damage and disruption; not all HIMs adequately capture all of the impactful attributes of volcanic hazards (G. Wilson et al., 2014). Therefore, the selection of an appropriate HIM is important. As discussed in Chapter 2 (Section 2.5.3.1), the selection of a HIM must consider: (1) the HIM's appropriateness to describe a range of infrastructure impact intensities; (2) the ease of HIM measurement in the field or laboratory; (3) the applicability of the HIM to hazard model outputs; and (4) which HIM has been used in existing impact datasets. The most common HIMs are: thickness or mass loading (tephra fall, PDC deposits, lahar deposits), dynamic pressure (PDC, lahar), flow height (lava flow, lahar), presence or absence (lava flow, gas emissions), density per unit area (ballistics), impact energy (ballistics) and concentration (gas emissions, tephra fall) (Tables 2.7–2.10).

4.4.4 Function derivation

The derivation of volcanic vulnerability and fragility functions requires: (1) data preparation to convert raw infrastructure impact data into data which can be used for function derivation; (2) a method to fit functions to available data, whether this be expert judgement or complex statistical approaches; and (3) justification for function applicability (i.e., is the derived function for a whole infrastructure sector or a specific component). These three aspects are discussed in turn in this section.

4.4.4.1 Data preparation

To derive volcanic vulnerability and fragility functions, some data preparation is required. For vulnerability functions, each data point needs to have a HIM and an IM value. Different IM values are described in Section 4.4.2 and are typically either a percentage value or normalised index. For fragility functions, each data point needs two attributes; (1) a HIM value which describes the volcanic hazard intensity; and (2) an IS (from Tables 2.11-2.14) which describes the impact intensity. Data are ordered by increasing HIM value and grouped into HIM bins, such that each bin has approximately the same number of data (Porter et al., 2007; Tarbotton et al., 2015). The probability of being equal to or exceeding each IS can be calculated for each HIM bin by counting the number of data which are greater than or equal to the IS of interest (see Table 4.3 for an example). Discrete HIM values are obtained by taking the median of each HIM bin. This method is used to derive fragility functions for electricity supply, water supply, wastewater and transportation networks primarily using post-eruption impact data and expert judgment (see Section 4.5).

Table 4.3: Example calculation of the probability of being equal to or exceeding different impact states (IS) for a tephra thickness bin between 1–10 mm using hypothetic data. The first two columns show the hypothetical tephra thickness and corresponding impact state. The third column provides the calculation and probability that the impact state experienced (is) is greater than or equal to IS_1, IS_2 and IS_3.

Hypothetic tephra thickness (mm)	Hypothetic impact state (IS)	Probability calculation
1	IS_0	$P(is \geq \mathrm{IS}_1) = \frac{8}{10} = 0.8$
2	IS_0	
3	IS_1	$P(is \geq \mathrm{IS}_2) = \frac{5}{10} = 0.5$
4	IS_1	
5	IS_2	$P(is \geq \mathrm{IS}_3) = \frac{1}{10} = 0.1$
6	IS_1	
7	IS_2	
8	IS_2	
9	IS_3	
10	IS_2	

4.4.4.2 Function fitting

Discrete or continuous mathematical functions can be fit to prepared impact data to obtain volcanic vulnerability and fragility functions. Because there are no methods to systematically derive volcanic vulnerability or fragility functions, a review of different function fitting methods from other natural hazard fields is required. At the simplest level, a function can be binary, such that below some hazard intensity threshold impact does not occur and above the threshold, impact occurs. For example, if lava is present, an asset (e.g., a road) may be considered completely destroyed and if lava is absent, the asset is undamaged. In this case the binary function would take the form:

$$y = \begin{cases} 0 & Hazard\ is\ absent \\ 1 & Hazard\ is\ present \end{cases} \tag{4.1}$$

where 0 represents no damage and 1 represents complete destruction.

Linear equations can also be used to define volcanic vulnerability and fragility functions. A linear function could be applied to the whole dataset or to individual segments. For the volcanic fragility functions derived in Section 4.5, I defined a fragility function for each IS with three linear equations. The start and end point of each line segment is defined by the available data points after the HIM binning process (see Section 4.4.4.1). I took this approach because the limited volcanic impact data only allowed three data points to be obtained from the binned HIM data, and using a complex mathematical equation to interpolate between data points is unjustified. The form of the segmented linear equations I used, and can be used in future, are shown in Equation (4.2):

$$y = \begin{cases} 0 & HIM = 0 \\ m_1 HIM + c_1 & k_1 \le HIM < k_2 \\ m_2 HIM + c_2 & k_2 \le HIM < k_3 \\ m_3 HIM + c_3 & k_3 \ge HIM \end{cases} \tag{4.2}$$

where m_1, m_2 and m_3 are slope constants and c_1, c_2 and c_3 are intercept constants for three linear equations. Constants k_1, k_2 and k_3, where $k_1 \neq k_2 \neq k_3$, are critical *HIM* values at which the different linear equations apply. Other mathematical equations, such as exponential and polynomial, can be used to define vulnerability and fragility functions; however, care must be taken with these, and with linear equations, as they are un-bounded on the x-axis and y-axis and could result in negative values or probabilities >1.

In other natural hazard fields, particularly earthquake and tsunami fields, the normal or lognormal cumulative distribution function (CDF) is commonly used to define fragility functions (Rossetto et al., 2013; Tarbotton et al., 2015). The form of the normal (Equation 4.3) and lognormal (Equation 4.4) CDF, respectively, are:

$$y = \Phi\left(\frac{x-\mu}{\sigma}\right) \tag{4.3}$$

$$y = \Phi\left(\frac{\ln(x) - \mu'}{\sigma'}\right) \tag{4.4}$$

where $\Phi(\cdot)$ is the standard normal CDF, μ/μ' is the mean and σ/σ' is the variance of the normal and lognormal CDFs, respectively. The lognormal CDF is used frequently for earthquake vulnerability assessments. Porter et al. (2007) and Rossetto et al. (2013) attribute its use to: (1) the function being constrained on the y-axis between 0–1 which is ideal for fitting probabilities bounded in this range; (2) the x-axis being constrained between 0–+∞ which prevents negative hazard intensities; and (3) is skewed to the left which better represents earthquake damage data clustered around low hazard intensities.

These mathematical equations can be fit to vulnerability and fragility data using statistical data fitting techniques, such as least squares or maximum likelihood estimation (see Baker (2014), Rossetto et al. (2014b), Lallemant et al. (2015), Tarbotton et al. (2015) and references therein for discussion and review of statistical data fitting techniques). Expert judgment can also be used to fit functions to limited or incomplete datasets or when simplifying complex problems. For expert judgment to be successful and transparent, I devised the following rules and general considerations for fitting functions to volcanic impact data. These rules are not explicitly used in research fields where sufficient data are available to derive vulnerability estimates (e.g., earthquake vulnerability assessment); however, are vital for volcanology where there are limited data to base vulnerability estimates on.

- Individual functions in a set are sequential, such that IS_i must be reached before IS_{i+1}. This allows the progressive accumulation of impact, for example, a building roof impacted by tephra fall must pass through light damage (IS_1) before complete destruction (IS_3).
- Individual functions in a set can converge but not intersect. Intersecting functions violates the above rule of sequential functions.

- A probability of 0 means impact is physically impossible to occur and conversely a probability of 1 means impact is certain, based on probability theory.
- No impact occurs when the HIM value is zero. This rule assumes normal infrastructure operation when volcanic hazards are absent.
- Functions are non-decreasing, i.e., functions do not decrease as the HIM value increases. This rule assumes the impact intensity is constant or becomes more intense as volcanic hazard intensity increases.
- Pre-condition (e.g., maintenance, age) of infrastructure sites can influence their vulnerability to volcanic hazards and functions should be modified for specific individual sites.
- Factors such as equipment typology, level of preparedness, mitigation strategies can influence volcanic vulnerability and functions should be tailored to individual infrastructure sites on a case-by-case basis to address these site specific factors.
- Different impact mechanisms can influence volcanic vulnerability and the interaction or dominance of different volcanic hazard impact mechanisms and should be considered.

All infrastructure sectors considered in Section 4.5 have limited (typically <20 data points), and often incomplete, post-eruption impact datasets. This meant that after data were aggregated into HIM bins, not all ISs were represented and when linear functions were fit to the data, the functions violated the above data fitting rules. Therefore, the functions were modified by expert judgment using the above rules, so that the data fitting rules were not violated and functions better represented the fragility of the infrastructure sectors to volcanic hazards. Figure 4.3 illustrates how the set of fragility functions for tephra fall impacts on the electricity transmission network was modified by expert judgment to prevent violation of data fitting rules.

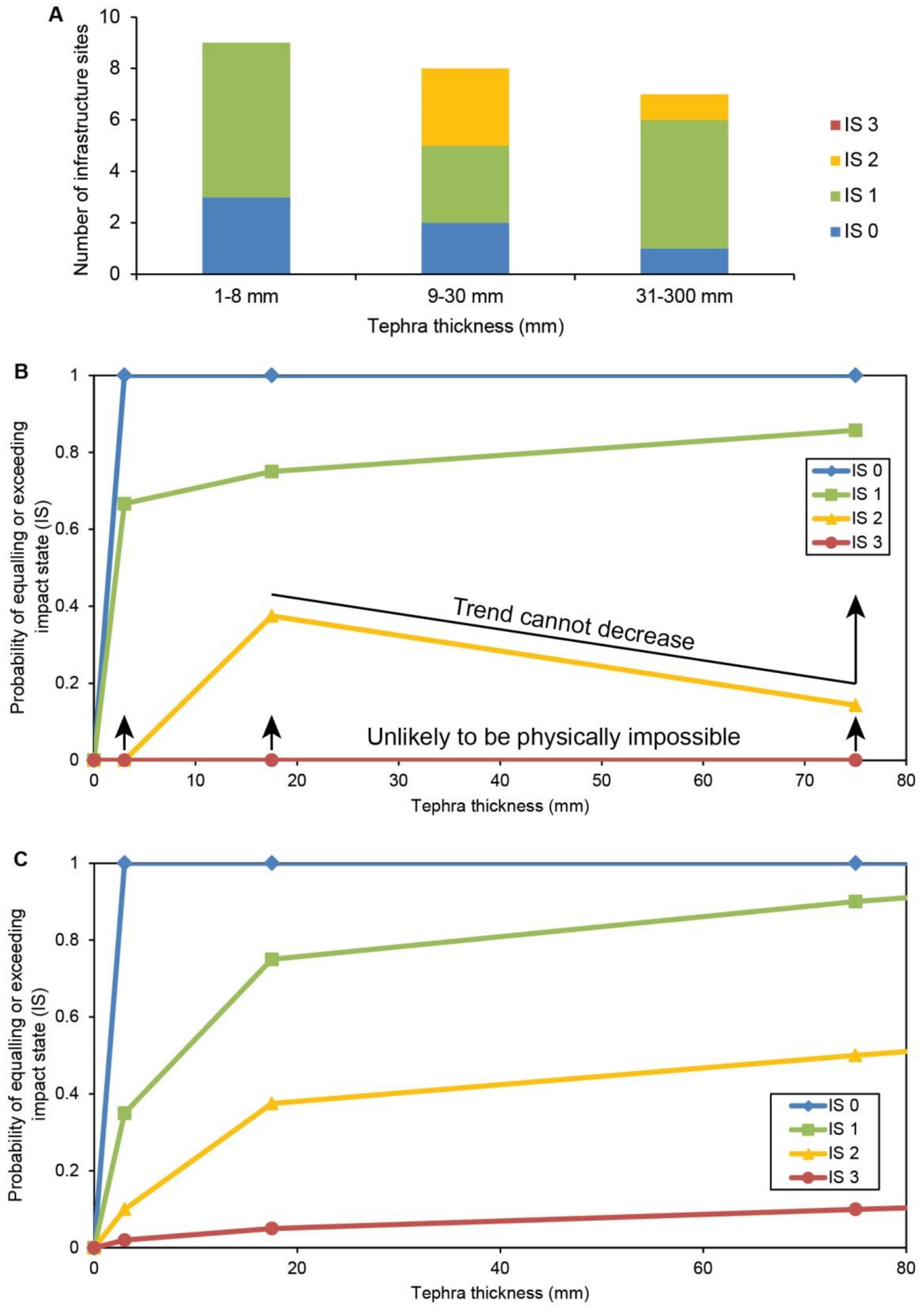


Figure 4.3: Steps to modify set of fragility functions for the electricity transmission network for tephra fall impacts. **A** histogram showing the number of available post-eruption impact data classified by IS for each tephra thickness bin. **B** fragility functions derived for each impact state (IS) from 24 post-eruption impact data points. Arrows indicate which data points need to be modified to avoid violating data fitting rules. **C** resulting fragility functions after modification by experts to prevent violation of data fitting rules.

4.4.4.3 Function applicability

Volcanic vulnerability and fragility functions can be derived for different hierarchical tiers of an infrastructure sector. Tiers are: the whole infrastructure sector (highest and most broad); sub-sectors; systems; and components (lowest and most narrow) (Figure 4.4). For example, a volcanic fragility function could be derived for an entire water supply sector (including water source, treatment plants and the pipe network) and/or for a specific type of water pump inside a water treatment plant (component). Functions can also be derived for different elements within the same tier. Using the above example, a function could be derived for an entire water supply network or multiple functions could be derived for each individual sub-sector (Figure 4.5). The decision for which tier(s) a function is derived for depends on a number of factors (Table 4.4) and justification of any decision should be provided with each function. System diagrams of infrastructure networks can aid in this decision.

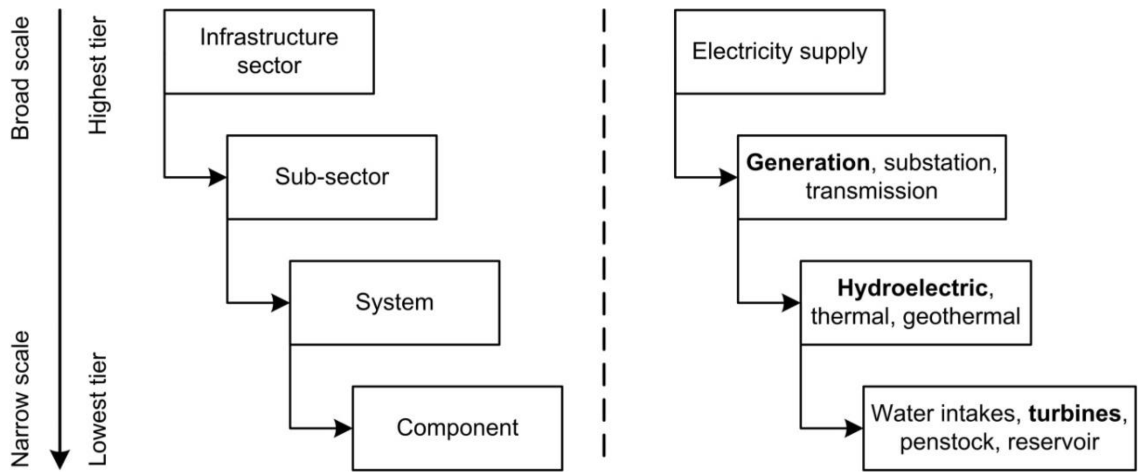


Figure 4.4: Critical infrastructure tier scheme with a hypothetical example from the electricity supply network (right). Bold typeface indicates which aspect is being assessed at each tier (in this example only).

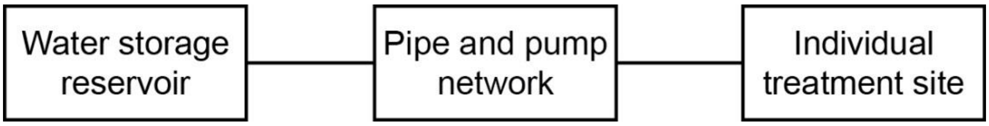


Figure 4.5: Simplified system diagram for a water supply network showing water storage, pipe network and treatment site sub-sectors. Volcanic fragility and vulnerability functions can be derived for any combination of sub-sectors.

Table 4.4: Description of factors which influence which infrastructure sector tier a volcanic vulnerability or fragility function can be derived for. Tiers are: the whole infrastructure sector (highest and most broad); sub-sectors; systems; and components (lowest and most narrow) (see Figure 4.4).

Factor	Description
Impact data source	Available volcanic impact datasets might relate to only individual infrastructure tiers or be an amalgamation of all tiers. For instance, post-eruption impact data may have only been collected or aggregated at specific infrastructure sector tiers or experimental impact data may be available only for specific components.
Impact data quantity	The quantity of volcanic impact data available can dictate which tiers functions can be derived for. Small datasets may not be able to be split into lower tiers, as there are too few data at each tier for function derivation. Large datasets which cover a range of tiers could be separated, allowing function derivation for individual tiers.
Expert judgment	The level of vulnerability knowledge and understanding experts have about a particular infrastructure sector/tier can influence which functions are derived. In-depth knowledge of infrastructure vulnerabilities to volcanic hazards allows the derivation of component-level functions.
Impact response	Different infrastructure aspects within the same tier might have different impact mechanisms or vulnerabilities, which could be neglected if not separated into lower tiers.
Function purpose	The purpose and end use of a function can dictate which infrastructure sector tier a function is derived for. A regional volcanic risk and vulnerability assessment requires an infrastructure sector approach, whereas a volcanic vulnerability assessment of an individual site might require component-level functions.
External factors	Volcanic vulnerability assessments (which require fragility and/or vulnerability functions) might be required by legislation, dictating which functions need to be derived.

4.4.5 Uncertainty analysis

When deriving volcanic vulnerability and fragility functions, there are a number of uncertainties which influence the quality of the resulting functions (Table 4.5). Aleatoric (statistical) uncertainty is introduced by the natural variation of volcanic eruptions, hazard occurrence, or the variation of infrastructure response to volcanic hazards. Different sources of epistemic (systematic) uncertainty are associated with HIMs and the volcanic impact dataset (Rossetto et al., 2014a). As discussed in Section 4.4.3, not all HIMs can adequately describe all the impactful aspects of a particular hazard. Therefore, a compromise is made when selecting a HIM for vulnerability and fragility functions introducing uncertainty. This could be overcome by deriving multiple volcanic function sets for different HIMs or combining multiple HIMs. In addition, most volcanic HIMs cannot be measured in real time and rely on measurements taken after an event, eye witness reports, and inference from volcanic deposits or impacts. For example, it is difficult to measure dynamic pressures of PDCs due to their potential to cause injury and destroy measurement equipment; therefore, the dynamic pressure is typically estimated from deposits or resulting asset damage (e.g., Jenkins et al., 2013). This can lead to large uncertainties in the measurement of volcanic hazard intensity (e.g., Engwell et al., 2013).

Large sources of uncertainty within volcanic impact data are from the classification of impacts into ISs and the sample size. Appropriate IS scales are required and need to be applied correctly to accurately assess infrastructure impacts from volcanic hazards. The use of different impact scales will result in the derivation of vulnerability and fragility functions which cannot be directly compared. The use of a standard volcanic impact scale, such as those presented in Tables 2.11–2.14, or the harmonisation of different volcanic impact scales to a standard scale is recommended (see Section 4.4.1.5). The number of observations in volcanic impact datasets can affect data interpretation and statistical analysis. Currently this is a large source of uncertainty for volcanic hazard vulnerability and fragility functions, with many datasets containing few data (~10s of data points). As a comparison, for earthquake fragility functions, Rossetto et al. (2014b) consider ~30 buildings for each building class as a minimum for function derivation and they recommend >100 buildings to be used.

Regardless of the source of uncertainty or its magnitude; identification, minimisation and quantification of all uncertainties should be performed. Rossetto et al. (2014a) considers this a fundamental step in the derivation of vulnerability and fragility functions for infrastructure assets.

Table 4.5: Sources of uncertainty for volcanic fragility and vulnerability functions for critical infrastructure.

Factor	Source of uncertainty
Hazard intensity metric (HIM)	Lack of observed and/or measured HIM.
	Incorrect measurement of HIM.
	Selection of appropriate HIM.
Impact data	Variation in impact of assets of similar typology for a given HIM.
	Uncertainty in the definition of ISs.
	Incorrect classification of observed impacts into ISs.
	Limited number of observations, spatial coverage and biased samples.
	Sampling methodology.
Asset data	Differences in asset vulnerability for the same asset typology.
	Incorrect identification of asset typology.
	Limited number of observations for each asset typology.
Function fitting	Data manipulation.
	Expert judgment biases.
	Selection of statistical model to represent function.

For the volcanic fragility functions derived in Section 4.5, uncertainty is accounted for at each HIM value by calculating the probability that an infrastructure site could be in one of four ISs. Variation in the HIM value is taken into account by binning these values and using the median bin value as discrete HIM values on each fragility plot. Other approaches, such as the use of confidence intervals (e.g., 5th and 95th percentiles), could be used to account for uncertainties, particularly with large data sets where these intervals can be statistically estimated.

4.4.6 Documentation

Documentation of volcanic vulnerability and fragility functions is important for their reproducibility, reliability and implementation. For functions to be used in volcanic vulnerability and risk assessments, users must understand what the functions show, how they were derived, their limitations and applicability. Transparency and understanding can be achieved by documenting the aspects in Table 4.6 for each (or set of) vulnerability and fragility function(s) for volcanic hazards. Documentation also provides the basis for review and updating of functions when further volcanic impact data becomes available.

Table 4.6: Aspects which must be documented for each (or set of) volcanic vulnerability and fragility function(s).

Required documentation aspect	Description
Infrastructure sector and sub-sector applicability	Which infrastructure sector and/or sub-sector have the functions been derived for and which sector they are applicable to.
Specific asset typology	Which specific asset typology (e.g., a specific type of water pump) have the functions been derived for or an indication if functions are for mixed typologies (e.g., all water pump designs).
Data source(s)	Source (bibliographic reference if available) of the volcanic impact data used to derive functions. If expert judgment was used, a description of how the judgment process was conducted is required.
Data quality rating	Overall quality of the impact dataset using the quality rating scheme in Table 4.2.
Number of observations	The total number of observations (data points) used to derive functions.
Impact metric (IM)	The impact metric used and justification for its use.
Hazard intensity metric (HIM)	The volcanic hazard intensity metric used and justification for its use.
Impact scale (IS)	The volcanic impact state scale used or if a new scale was developed, a description of each impact state and justification for its use.
Function form, fitting and manipulation	The mathematical form of the functions used (e.g., linear, lognormal CDF, binary), the fitting technique used (e.g., linear regression, least-squares, expert judgment) and any data manipulation performed.

Required documentation aspect	Description
Assumptions	Discussion of any and all assumptions and decisions made during the process of data manipulation and function fitting.
Uncertainties	Discussion and identification of the uncertainties associated with the derived functions and how they are accounted for.
Limitations	Discussion of any and all limitations of the derived functions. In particular, limitations which indicate what the function should not be used for.

4.5 Volcanic tephra fall fragility functions

4.5.1 Overview

In this section I present fragility functions for discrete tephra fall impacts to the electricity supply (Section 4.5.3), water supply (Section 4.5.4), wastewater (Section 4.5.5) and transport networks (Section 4.5.6). Buildings are not included here as a number of studies (e.g., Spence et al., 2005; Zuccaro et al., 2008; Jenkins and Spence, 2009; Maqsood et al., 2014) have already derived fragility functions for different building typologies and this is not the focus of my thesis. This section focuses on tephra fall as it is the most common and widespread volcanic hazard (T.M. Wilson et al., 2012). In addition, there are more tephra fall impact data available with which to derive fragility functions.

4.5.2 Methodology overview

The functions presented here have been derived using the methodology described in Section 4.4, with a brief summary provided here.

The HIM used for all functions in this section is tephra thickness. Thickness is used because the majority of post-eruption impact assessments record tephra thickness, as it is an easy quantity to measure in the field. Thickness is also a common output of tephra hazard models, which allows direct relation between hazard and vulnerability for risk estimation. The IM used for fragility functions is the probability of being equal to or exceeding an IS (ISs are defined in Table 2.12). Impact states are used because most post-eruption impact data provide qualitative descriptions of impacts, rather than quantitative values of impact intensity. The qualitative descriptions of damage and function loss are used to assign an IS for each impacted site, providing a semi-quantitative estimate of impact intensity. Based on tephra thickness, data are aggregated into at least three thickness bins and the probability of being equal to or exceeding each IS is calculated. Probabilities for each IS are plotted against median tephra thickness for each bin and segmented linear functions are fit to data for each IS using Equation (4.2). Each set of fragility functions comprises four individual functions; one for each of IS_0–IS_3. Expert judgment is used to modify fragility functions if they violate the data fitting rules outlined Section 4.4.4.2. A segmented linear function is used; because after data aggregation, due to the limited available impact data, only three data points for each IS are obtained. Using a complex mathematical function to interpolate between so few data points is unjustified at this time. Each set of fragility functions is accompanied by a histogram plot which shows the available impact data, mapped to ISs, which are used to derive each function.

For each set of fragility functions, the required documentation from Section 4.4.6 is included, in addition to commonly observed impacts (further details can be found in Chapter 2 and figures therein), vulnerable components and key knowledge gaps. These additional sections provide the context in which the functions are derived and identify areas for future research.

4.5.2.1 Caveats

The following caveats apply to all fragility functions in this section:

- Presented fragility functions are for discrete infrastructure sites and only consider generic infrastructure design and typology due to limited vulnerability data on specific typologies. Vulnerability will be different when considering different typologies and sites; therefore, functions should be tailored on a site-by-site basis.
- Interdependencies between infrastructure sectors are not considered; each sector is assessed in isolation. Interdependencies between sectors are complex and will likely influence overall vulnerability.
- Presented fragility functions only consider discrete tephra fall events and not prolonged or reoccurring tephra falls, nor clean-up and restoration of infrastructure sectors following tephra fall.

4.5.3 Electricity supply network

Electricity supply networks comprise electricity generation sites, substation sites and transmission networks. While these three sub-sectors are part of the same network they differ in the type of equipment used and resulting tephra impact mechanisms; therefore, are considered separately. Commonly observed tephra fall induced impacts are: insulator flashover; breakage of transmission lines; abrasion of turbines and cooling systems at generation sites; and disruption of service at substations. See Section 2.4.1 for further discussion of impacts to electricity supply networks.

4.5.3.1 Available tephra fall vulnerability data

The majority of the vulnerability data for electrical networks impacted by tephra falls comes from post-eruption impact assessments. There are data for at least 10 eruptions dating back to the 1980 Mt. St. Helens eruption; summarised in Section 2.4.1 and by Wardman et al. (2012b). The majority of these data report impacts to transmission and distribution networks, although there are some data for generation and substation sites. The data are primarily qualitative and document disruption and damage as a function of tephra fall intensity. Wardman (2013) conducted systematic laboratory experiments to determine the probability of insulator flashover as a function of tephra thickness and moisture content. Experiments to document flashover were conducted in a controlled environment using different insulator types common in New Zealand with both dry and wet tephra. Other experimental research on tephra induced insulator flashover was conducted by Nellis and Hendrix (1980) and Matsuoka et al. (1995). Laboratory experiments by Zorn (2014) were conducted to determine changes in solar panel performance as a function of increasing tephra thickness; however, this study is limited in its extent and is not used here.

Quality rating of vulnerability data

Table 4.7: Quality rating of available tephra fall impact data for each electricity sub-sector and asset. See Section 4.4.1.6 for quality rating scheme.

Sub-sector	Assets	Quality rating
Generation sites	Hydroelectric power (HEP)	C
	Thermal power	D
	Geothermal power	D
Substations	Whole site	C
	Insulators	B
	Transformers/switch gear	C
	Control systems	C
	Gravel ground cover	C
Transmission	Insulators	B
	Conductors (lines)	C

Vulnerable components matrix

Table 4.8: Impact modes and factors which influence vulnerability to tephra fall for different electricity network assets.

Sub-sector	Assets	Impact modes	Factors which influence vulnerability
General	All assets	Cascading failure of electrical transmission network due to impact at individual sites.	Interdependency and connectedness of electrical transmission components and networks.
Generation sites	Hydroelectric power (HEP)	Abrasion of turbines. Contamination and blockage of control systems. Sedimentation in storage reservoirs.	Turbine design (shape, material). Reservoir catchment size and volume. Turbine bypass systems (is tephra contaminated water able to bypass turbines).
	Thermal power	Abrasion and blockage of air intakes and cooling systems. Contamination and blockage of control systems. Contamination of fuel supplies.	Cooling system (condenser) design.
	Geothermal power	Abrasion and blockage of air intakes and cooling systems. Contamination and blockage of control systems.	Cooling system design.
Substations	Whole site	Contamination and abrasion of sensitive equipment and control systems. Contamination of gravel ground cover.	Substation location and whether it is covered (i.e., inside a building) or not.
	Insulators	Insulator flashover.	Operating voltage. Insulator orientation (vertical or horizontal). Insulator design (material, profile).
	Transformers/switch gear	Abrasion and contamination of switching components.	Transformer design. Design of moving parts.

Sub-sector	Assets	Impact modes	Factors which influence vulnerability
	Control systems	Contamination of control systems.	Design of control system.
	Gravel ground cover	Contamination and resistivity changes of gravel ground cover.	Design resistivity level.
Transmission	Insulators	Insulator flashover.	Operating voltage. Insulator orientation (vertical or horizontal). Insulator design (material, profile). Whether lines are above or below ground.
	Conductors (lines)	Loading of lines.	Operating voltage. Static load rating. Whether lines are above or below ground.

Key knowledge gaps

- Performance of HEP stations during and after tephra fall, in particular the rate at which turbine abrasion occurs and how the catchment area and reservoir volume influence tephra transport to the turbines.
- Performance of open air and water cooling systems exposed to different doses of tephra at thermal and geothermal power stations.
- Performance of air intake systems and filter setup for thermal power stations.
- Influence of various substation equipment (transformers, circuit breakers, capacitors) for the overall vulnerability of substations during tephra fall.
- Wind turbine blades abrasion occurrence and rate.
- Performance and abrasion damage of solar panels.

4.5.3.2 Fragility functions

Electricity generation

Tephra can affect the generation of electricity through impacts to the cooling systems of thermal power stations and through abrasion of HEP turbines. These impacts can cause disruption to electricity generation.

Due to the size and scale of equipment used at electricity generation sites, no experiments have been undertaken to systematically determine the vulnerability of these to tephra fall. In this case, the fragility functions presented here are based on post-eruption impact assessment data. Twelve case studies documenting impacts to different generation types are available and Figure 4.6A shows that the majority are classified as IS_1 with no documented cases of IS_3.

Impact mechanisms for the three generation types considered here are fundamentally different; however, there are insufficient data to derive appropriate fragility functions for each generation type. Therefore, all data are used, in association with expert judgment to avoid violating data fitting rules, to derive a set of fragility functions (Figure 4.6B) for mixed-generation types (i.e., this set of functions can be used to calculate the fragility of a HEP, thermal or geothermal power stations). While no available case studies document impacts at IS_3, I assume they are likely to occur in future eruptions and therefore IS_3 has been included in the fragility function with a probability <0.2.

Here I provide a brief summary of some of the vulnerability differences between each generation type which can inform, along with addition tephra fall impact data, specific generation type vulnerability assessments in future research. At HEP stations, water, which could be contaminated with tephra, is in direct contact with the turbines which could lead to abrasion damage reducing turbine efficiency (e.g., Meredith, 2007). At thermal and geothermal power stations, turbines are typically steam driven and are closed systems, such that tephra would be unlikely to be in direct contact with the turbine; reducing the potential for abrasion. Therefore, for a given tephra thickness, the probability of each ISs for HEP stations is likely to be slightly higher than for thermal and geothermal power stations.

Some impacts are dependent on the concentration (or 'dose') or tephra received over time. This is typically the case for abrasion damage to HEP turbines. For example, during the 1995 Mt. Ruapehu eruption, tephra fell in the Rangipo catchment and passed through two turbines at the nearby power station. Immediately after the eruption there was no damage and the turbines remained in operation for six months before the station was temporarily shut down after significant turbine abrasion occurred (T.M. Wilson et al., 2012). For the majority of the HEP data here, impacts occurred between 6–12 months after the eruption. With additional research regarding the occurrence of abrasion damage (a key knowledge gap), time and/or 'dose' based fragility functions may be able to be derived, providing better estimates of vulnerability over time.

Geothermal and thermal stations require air for cooling and combustion, the latter for thermal stations. These systems may sustain abrasion or filters may become blocked over time. Again this depends on the 'dose' of tephra these systems receive over time; an aspect that is not currently well understood and requires further investigation before appropriate vulnerability estimates can be made.

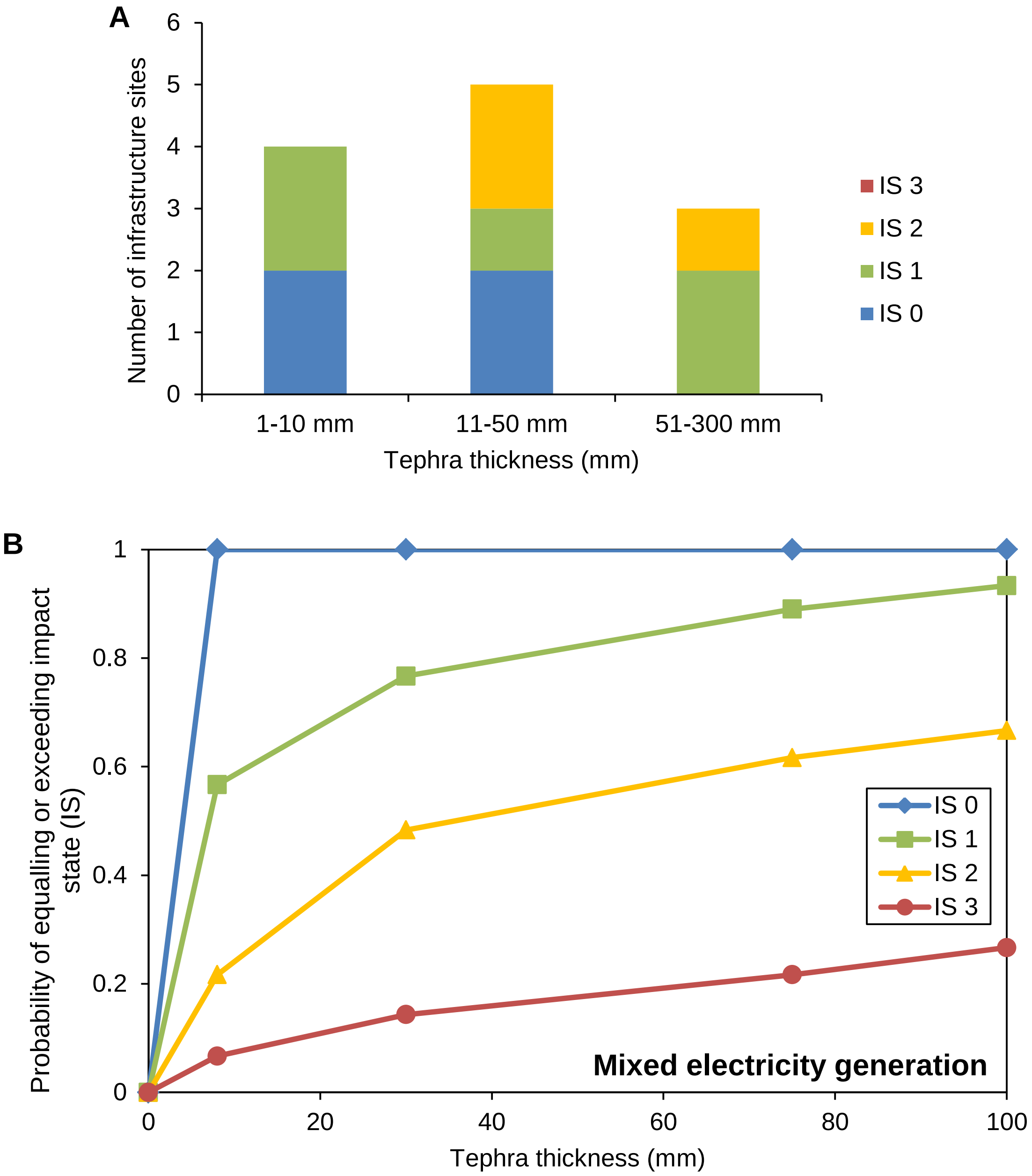


Figure 4.6: Mixed electricity generation types (hydroelectric, geothermal and thermal): **A** histogram showing the number of available post-eruption impact data classified by IS for each tephra thickness bin; **B** set of fragility functions for mixed electricity generation types showing probability of equalling or exceeding each IS for tephra thickness.

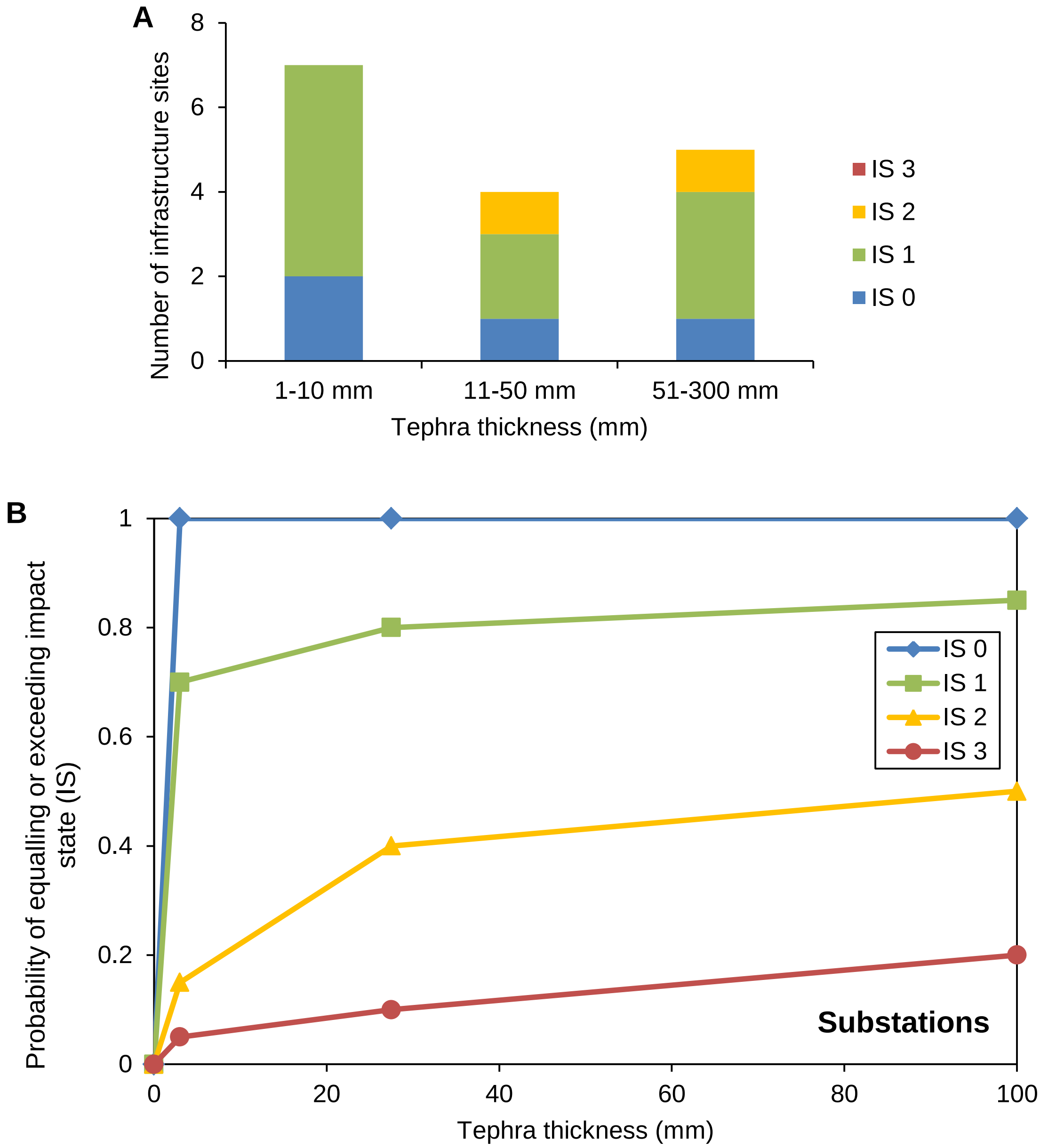


Figure 4.7 Electricity substations: **A** histogram showing the number of available post-eruption impact data classified by IS for each tephra thickness bin; **B** set of fragility functions for electricity substations showing probability of equalling or exceeding each IS for tephra thickness.

Substations

Substations are vulnerable to tephra fall due to the range of sensitive equipment they contain. There are 16 post-eruption impact assessments available to derive a set of fragility functions for tephra fall impacts. I am unaware of any experimental data for substation components, likely due to difficulties in conducting experiments with the complex and often large equipment. The majority of the post-eruption impact data are classified as IS_1, cleaning required, (Figure 4.7A) as a result of operators cleaning gravel ground cover or sensitive equipment such as transformers. Few instances of substation impact $\geq IS_2$ have been documented (Figures 2.4 and 4.7A) indicating that cleaning related impacts are more common than equipment damage. However, like generation sites, IS_3 is likely to occur in future eruptions and is therefore estimated with a probability ≤ 0.15 in the fragility function (Figure 4.7B). The higher likelihood of a substation being at IS_1 is represented in Figure 4.7B with the IS_1 fragility function retaining a probability of between 0.3–0.6 for any given tephra thickness.

Electricity transmission lines

Electricity transmission lines are vulnerable to tephra fall impacts resulting in permanent or temporary disruption of electricity supply. The majority of the 24 post-eruption impact data points are classified as requiring cleaning (IS_1) to be reinstated (Figure 4.8A). Disruption is typically cause by flashover (the most common impact observed; Wardman et al., 2012b), controlled shutdowns to prevent damage and cleaning of equipment. Physical damage such as line breakage (IS_2) has occurred in three previous eruptions (Figure 2.4), however more intense damage (IS_3) has not been documented, although could occur in future eruptions. In addition to these post-eruption impact data, Wardman et al. (2012b) and Wardman (2013) conducted laboratory experiments to investigate the occurrence of tephra induced flashover. Insulator flashover occurred at all tephra thicknesses when wet tephra accumulated on insulator surfaces. Insulator flashover is classified as IS_1, and therefore, I used the Wardman et al. (2012b) flashover fragility function to inform and modify the IS_1 function. A set of tephra fall fragility functions for transmission lines is shown in Figure 4.8B. These functions are derived from all known impacts to transmission lines and estimate the probability of each ISs as a function of tephra thickness.

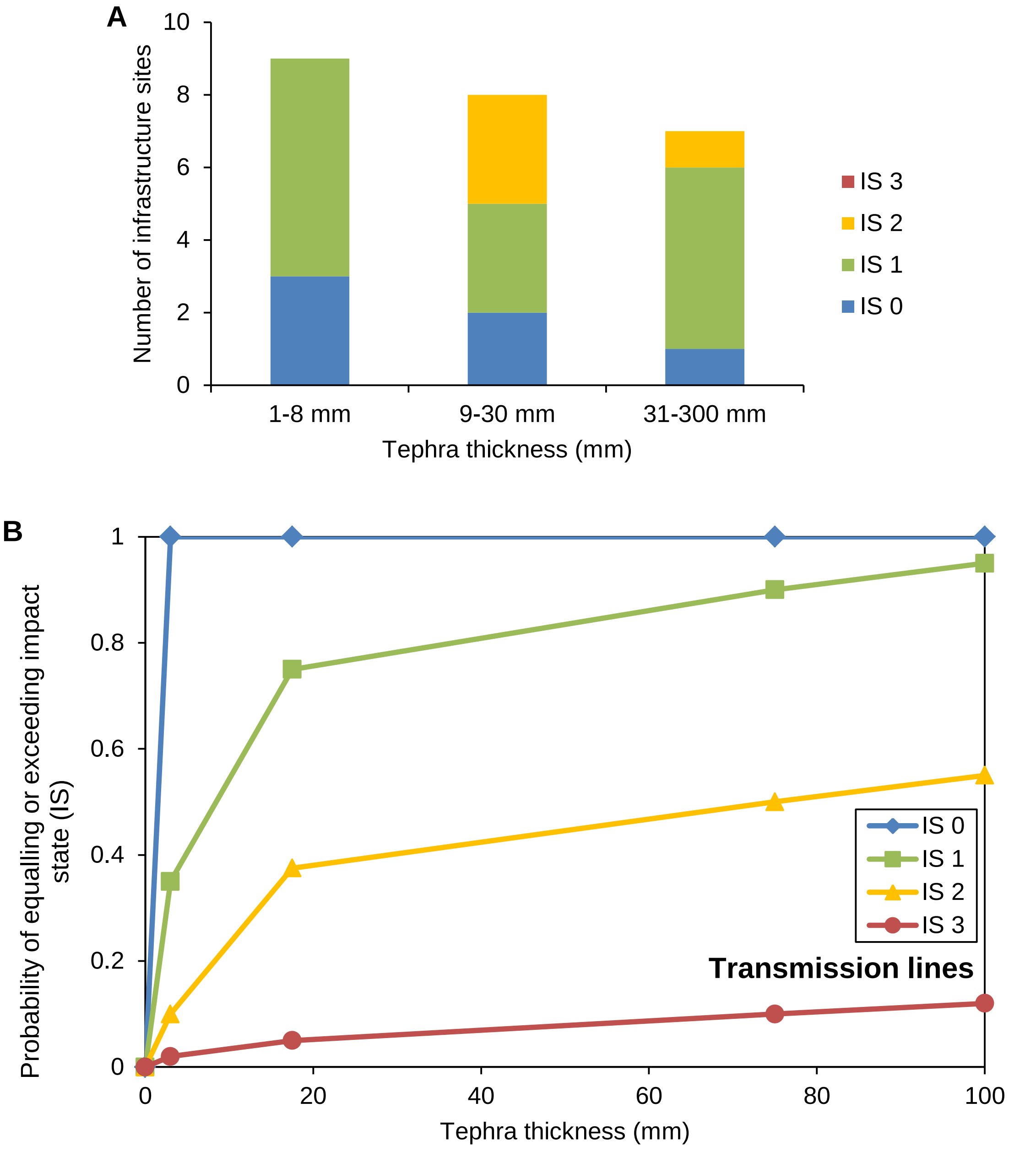


Figure 4.8: Electricity transmission lines: **A** histogram showing the number of available post-eruption impact data classified by IS for each tephra thickness bin; **B** set of fragility functions for electricity substations showing probability of equalling or exceeding each IS for tephra thickness.

4.5.4 Water supply networks

Water supply networks include water source areas (rivers, lakes, and groundwater), water treatment, storage facilities and distribution networks (above or below ground). Impacts commonly caused by tephra fall are: changes in water quality (chemical and turbidity changes); increased water demand (typically for tephra clean-up); abrasion of pumps; and blockage of filters at treatment plants. See Section 2.4.2 for further discussion of impacts to water supply networks.

4.5.4.1 Available tephra fall vulnerability data

The majority of the available vulnerability data for water supply networks comes from 14 post-eruption impact assessments from 1980 (Mt. St. Helens, USA) to the present; summarised in Section 2.4.2 and by Johnston et al. (2004), Stewart et al. (2009) and T.M. Wilson et al. (2012). These assessments are of variable quality and detail; they are predominantly qualitative data sets describing both disruption and physical damage. Studies by Hindin (1981), Stewart et al. (2006) and White et al. (2011) have quantitatively assessed impacts to water quality (chemical contamination and turbidity) through numerical modelling and laboratory experiments. I am unaware of any quantitative studies on the physical impacts of tephra fall to water treatment and distribution networks.

Quality rating of vulnerability data

Table 4.9: Quality rating of available tephra fall impact data for each water supply sub-sector and asset. See Section 4.4.1.6 for quality rating scheme.

Sub-sector	Assets	Quality rating
Water source	General	C
Pipe network	Pipes	D
	Pumps	C
Treatment plant	Whole site	C
	Water quality	B

Vulnerable components matrix

Table 4.10: Impact modes and factors which influence vulnerability to tephra fall for different water supply assets.

Sub-sector	Assets	Impact modes	Factors which influence vulnerability
Water source	General	Contamination of raw source water.	Whether source water is an open water body or groundwater.
	Intake structure	Blockage and abrasion of intake structure.	Intake design and materials. Automatic intake shutdown system.
Pipe network	Pipes	Blockage of pipes.	Pipe capacity, design and sediment load.
	Pumps	Abrasion and blockage of pumps.	Pump design and material. Pump capacity and throughput.
Treatment plant	Coagulation	Treatment disruption.	Treatment strategy. Plant design.
	Clarification	Abrasion of mechanical components. Infilling of tanks.	Design and materials of components. Tank capacity, surface area and roof design.
	Filtration	Blockage of filters.	Filter design.
	Disinfection	Abrasion of ultra violet lights. Blockage of filters. Impacted water quality.	Design and materials of components. Finished water quality requirements.
	Whole site	Abrasion and blockage of pumps. Power loss to treatment facility.	Pump design and materials. Pump capacity and throughput.

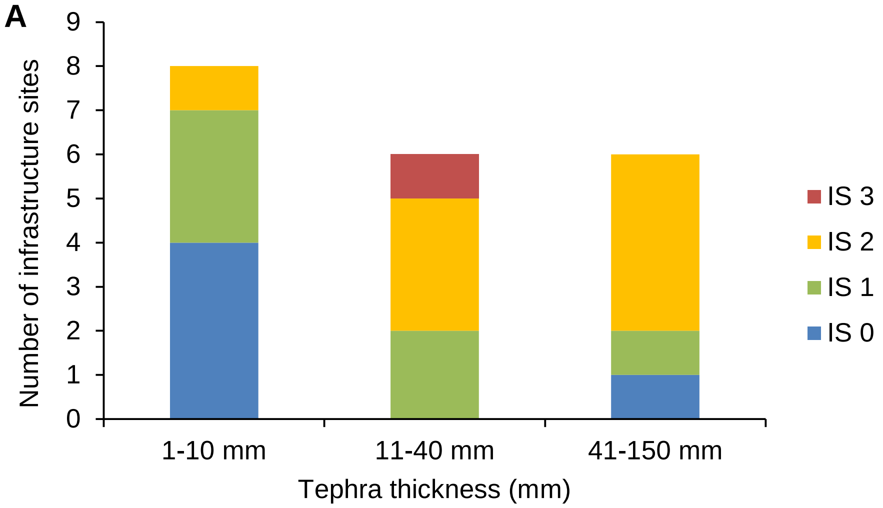
Key knowledge gaps

- How the catchment area, reservoir volume and surface hydrology influence tephra settling and transport through reservoir to intake structures.
- The process by which tephra moves through water treatment plants and pipe networks.
- The process and occurrence of tephra induced abrasion and mechanical failure of water pumps and intake structures.
- Progressive blockage and decreased efficiency of water filters and screens.

4.5.4.2 Fragility functions

Tephra fall can impact water supply networks causing both disruption and physical damage. Analysis of post-eruption impact data shows that the most common impact intensity is IS_2 followed by IS_1 (Figure 4.9A). There is one instance of IS_3 from Pacaya where some above-ground pipes suffered damage from large tephra particles (Wardman et al., 2012a). This is also the only instance of pipe damage documented from previous eruptions. Because there is only one instance of pipe damage, the set of fragility functions I derive here are for individual treatment plants and not the pipe network(s). The pipe network is likely to be more resilient to tephra fall impacts as they are commonly underground; however, further research would confirm this. Although, tephra deposited into water sources may be transported through the pipe network into the treatment plant. Tephra arriving at the treatment plant in this manner will influence vulnerability, likely increasing vulnerability. Until further research investigates this aspect, the functions in Figure 4.9B are for direct tephra fall at a treatment plant. Figure 4.9B shows that for thin tephra falls there is a higher probability of tolerance (IS_0) and disruption type impacts (IS_1). As tephra thickness increases there is a higher probability of a water treatment plant being at IS_2, reflecting the higher occurrence of these impacts during previous eruptions. While there are limited data to assess the probability of IS_3, I assume that as tephra thickness increases, the probability of IS_3 will also increase as a result of the increase likelihood of tephra induced abrasion of pumps. Figure 2.7A shows that abrasion damage on pumps and other mechanical components is more likely at tephra thicknesses ≥30 mm than <30 mm.

A limitation of this set of fragility functions is the time taken for abrasion damage and filter blockage to occur is not accounted for. These impact types are controlled by the tephra concentration (or ‘dose’) components are exposed to over time, which is currently poorly understood. Therefore, discretion must be used when applying the derived functions (Figure 4.9B) as higher ISs (IS_2, IS_3) are likely to occur sometime after a tephra fall event. In addition, water treatment plants can be highly specialised and specifically designed for the local/regional water characteristics. Each of the 20 post-eruption instances of water supply impact occurred at a slightly different treatment plant, the subtlety of these differences has been lost in deriving these functions (Figure 4.9B). Therefore, a recommendation is made that fragility functions be derived specifically for each water treatment site on a case-by-case basis to improve vulnerability assessments.



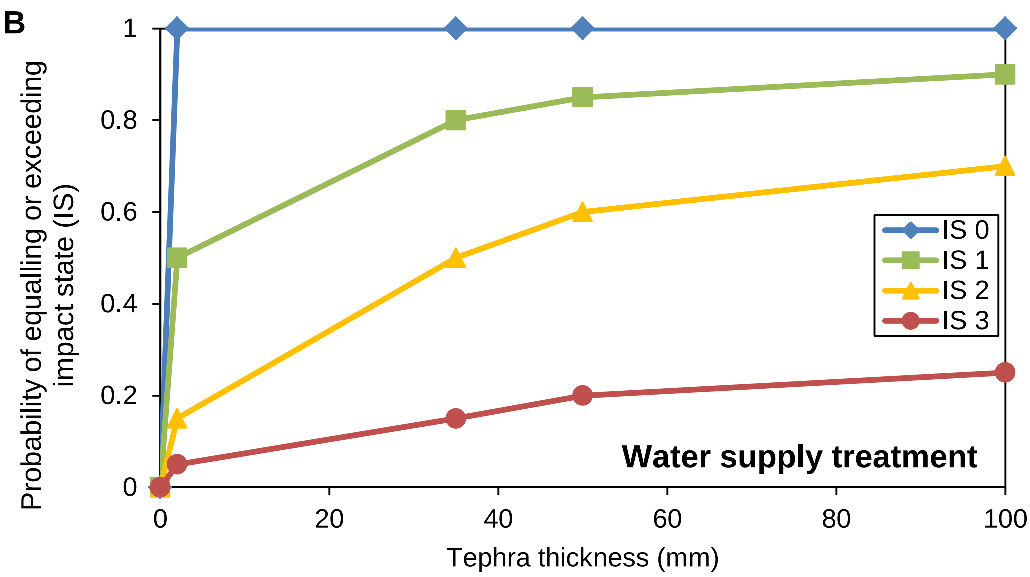


Figure 4.9: Water supply treatment plant: **A** histogram showing the number of available post-eruption impact data classified by IS for each tephra thickness bin; **B** set of fragility functions for water supply treatment plant site (not including the influence of tephra deposited in water sources or transported through pipe networks) showing probability of equalling or exceeding each IS for tephra thickness.

4.5.5 Wastewater treatment network

Wastewater networks comprise a network of underground collection pipes, pumps and above-ground treatment facilities. Wastewater networks may be combined with stormwater systems or the two may be completely separate, with the former configuration increasing the vulnerability of the overall network (Barnard, 2009). Impacts commonly caused by tephra fall are: abrasion of pumps and mechanical components; pipe blockages; and treatment disruption (collapse of biological processes) which could result in the bypassing of untreated wastewater. See Section 2.4.3 for further discussion of impacts to wastewater networks.

4.5.5.1 Available tephra fall vulnerability data

The two primary vulnerability data sets available for wastewater networks are post-eruption impact assessments and laboratory experiments. Impact assessments come from a limited number of eruptions (eight in total) between 1980 (Mt. St. Helens) and 2011 (Puyehue-Cordón Caullé) and are summarised in Section 2.4.3 and Barnard (2009). The only quantitative data I am aware of is the analogue laboratory experiments undertaken by Barnard (2009). Due to the size and cost of large wastewater treatment pumps, Barnard (2009) examined pump abrasion on smaller effluent pumps commonly used in agricultural settings. While these experiments cannot be directly compared to wastewater pumps, they can provide insight as to the potential impacts and guide any expert judgment.

Quality rating of vulnerability data

Table 4.11: Quality rating of available tephra fall impact data for each wastewater sub-sector and asset. See Section 4.4.1.6 for quality rating scheme.

Sub-sector	Assets	Quality rating
Pipe network	Pipes	D
	Pumps	C
Treatment	Whole site	C

Vulnerable components matrix

Table 4.12: Impact modes and factors which influence vulnerability to tephra fall for different wastewater network assets.

Sub-sector	Assets	Failure modes	Factors which influence vulnerability
Pipe network	Pipes	Blockage of pipes.	Pipe capacity, design and sediment load.
	Pumps	Abrasion and blockage of pumps.	Pump design and material. Pump capacity and throughput.
Treatment	Primary treatment	Blockage of filters. Abrasion of sediment scrapers. Infilling of tanks.	Design and material of scrapers. Tank capacity, surface area and roof design.
	Secondary treatment	Infilling of tanks. Impact on bacterial processes.	Tank capacity, surface area and roof design. Treatment strategy.
	Whole site	Abrasion and blockage of pumps. Power loss to treatment facility.	Pump design and materials. Pump capacity and throughput.

Key knowledge gaps

- Ingress of tephra into underground stormwater and wastewater pipe networks.
- The influence of combined wastewater-stormwater networks on the overall vulnerability of wastewater networks.
- The process by which tephra moves through wastewater treatment plants and pipe networks and the development (in time and space) of pipe blockages.
- The process and occurrence of tephra induced abrasion and mechanical failure of wastewater pumps.
- Progressive blockage and decreased efficiency of filters and screens.

4.5.5.2 Fragility functions

Analysis of the available post-eruption impact data shows that the most common impact intensities are IS_1 and IS_2 (Figure 4.10A). IS_3 has also been documented at tephra thicknesses between 5–25 mm after the 1980 Mt. St. Helens eruption. In this case the Yakima Wastewater Treatment Plant suffered severe abrasion damage to pumps and pumping components and the treatment plant was bypassed which resulted in the discharge of untreated waste into the Yakima River (Blong, 1984). While these impacts are documented as occurring with tephra thicknesses between 5–25 mm (given by isopach maps), significantly more tephra likely passed through the treatment plants as tephra was being washed into the stormwater network (Blong, 1984). Therefore, the probability of exceeding IS_3 increases as tephra thickness increases (Figure 4.10B). However, for thicknesses >10 mm, there is a higher probability of a site being at IS_2. This trend is influenced by the post-eruption impact data which contain a number of older wastewater networks which are combined with stormwater networks. Tephra can enter stormwater networks though drainage systems, introducing additional tephra into the wastewater treatment plant, leading to increased impact at lower recorded tephra thicknesses. This limitation of the derived functions is difficult to overcome with available data which does not record volume of tephra entering a treatment facility. By obtaining additional data which combines tephra volume and exposure time, vulnerability assessments will improve; however, this data is difficult to obtain.

In modern wastewater systems, the stormwater network is typically separate. In this case the wastewater network is effectively a closed system and tephra is less likely to arrive at the treatment plant though the pipe network, increasing overall resilience. Tephra may still accumulate at the plant through direct air fall. Because there is a limited understanding of how tephra moves enters and moves through wastewater pipe networks, the fragility functions in Figure 4.10B are derived for individual treatment sites and do not consider the influence of tephra entering through the pipe network. Until further research investigates this aspect, the functions in Figure 4.10B are for direct tephra fall at a treatment plant.

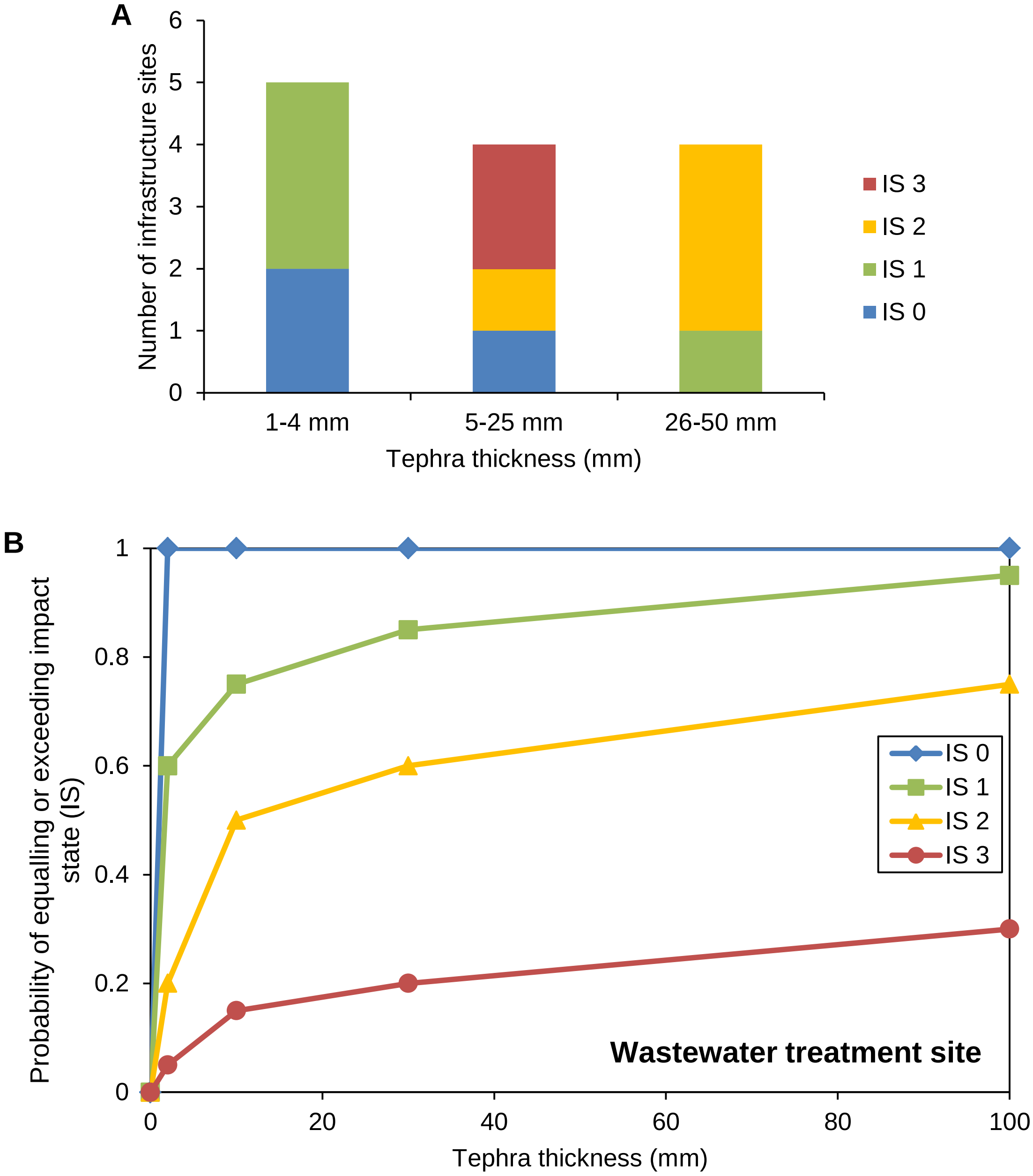


Figure 4.10: Wastewater treatment plant: **A** histogram showing the number of available post-eruption impact data classified by IS for each tephra thickness bin; **B** set of fragility functions for wastewater treatment plant site (not including the influence of tephra entering and being transported through pipe networks) showing probability of equalling or exceeding each IS for tephra thickness.

4.5.6 Transportation networks

Transportation networks include those on land, air and sea, the latter not considered here due to very limited tephra fall impact data. Typically, these include large expansive linear networks (roads, railways), nodes (airports, ports) and vehicles (cars, trains). This section excludes vehicles, trains, aircraft and support buildings (e.g., airport terminals and train stations). Impacts commonly caused by tephra fall include: reduction in visibility and traction; covering of roads and runways; and vehicle damage (abrasion, filter blockage, seized engines). See Section 2.4.4 for further discussion of impacts to transportation networks.

4.5.6.1 Available tephra fall vulnerability data

The majority of the available transport vulnerability data are from post-eruption impact assessments and media reports and are typically qualitative (Figure 2.9A). To date there are limited quantitative data relating different impact types to tephra thicknesses. Barnard (2009) undertook a number of semi-quantitative experiments to determine the difficultly of driving on tephra covered roads, primarily on the slopes of Mt. Etna, Italy, and laboratory experiments are currently being conducted to quantitatively examine the skid resistance (traction) on tephra covered roads and visibility reduction during tephra falls (D. Blake, pers. comm., 2015). Large databases have been compiled documenting impacts to airports between 1944–2006 (Guffanti et al., 2008) and aircraft between 1953–2009 (Guffanti et al., 2010). A number of experiments have been undertaken to examine tephra impacts, particularly engine damage, to aircraft inflight (e.g., Drexler et al., 2011; Dunn, 2012; Shinozaki et al., 2013; Davison and Rutke, 2014; Song et al., 2014). Impacts to rail networks are the least documented, with the only available data from eruptions of Soufrière St. Vincent (1902), Mt. St. Helens (1980) and Shinmoedake (2011) (Figure 2.9A).

Quality rating of vulnerability data

Table 4.13: Quality rating of available tephra fall impact data for each transport sub-sector and asset. See Section 4.4.1.6 for quality rating scheme.

Sub-sector	Assets	Quality rating
Road	Road	B
	Vehicle	C
Rail	Track	D
	Train	D
Air	Airport	C
	Aircraft (inflight)	B

Vulnerable components matrix

Table 4.14: Impact modes and factors which influence vulnerability to tephra fall for different transportation assets.

Sub-sector	Assets	Failure modes	Factors which influence vulnerability
Road	Road	Loss of traction. Covering of markings. Loss of visibility.	Road surface composition and level of maintenance. Road inclination.
	Vehicle	Abrasion damage. Clogging of filters. Loss of visibility.	Vehicle design. Type of filters.
Rail	Track	Loss of traction. Loss of electrical communication and engine signals. Disruption to track switches.	Track design and material. Communication method between train and control stations.
	Train	Abrasion damage. Clogging of filters. Loss of visibility.	Train design. Type of filters.
Air	Airport	Loss of traction. Covering of markings and lights. Loss of visibility.	Runway surface and level of maintenance.
	Aircraft (inflight)	Loss of engine thrust. Abrasion of turbine blades, windshields and sensors.	Aircraft design. Aircraft altitude.

Key knowledge gaps

- Quantification of reduction in visibility and traction during tephra falls for all type of transportation.
- Abrasion damage of paved surfaces (roads, runways) cause by direct tephra fall and during tephra clean-up.
- Abrasion damage occurrence on train wheels and railway tracks.
- Failure of electric and non-electric rail signals and switches.

4.5.6.2 Fragility functions

Road transportation

Tephra fall can cause disruption to the road network and can lead to traffic accidents, reduction in speed and possible road closure. Due to the limited number of quantitative experimental data regarding impacts to the road network, post-eruption impact data are used to derive road fragility functions. The majority of the available post-eruption impact data can be classified as IS_1 (Figure 4.11A), suggesting that in most cases loss of traction, visibility and possible abrasion will occur. Typically these impacts occur with thin (~2–3 mm) tephra deposits (Figure 2.9A) and therefore, disruption of road transportation is common in distal areas. In a number of cases roads have been closed; however, this is typically controlled by authorities' risk tolerance and safety protocols. The set of fragility functions (Figure 4.11B) reflect the tendency for more sites at IS_1 across all tephra thicknesses, as it has the highest occurrence probability. At 100 mm there is a probability of 0.15 that a road remains in IS_0. Post-eruption data and experiments by Barnard (2009) suggest that in some cases vehicles can drive through tephra deposits between 50–100 mm thick, albeit at a reduced speed. The only available impact assessment for IS_3 is from the 2008 Chaitén eruption where a non-engineered bridge sustained significant damage after ~200 mm of tephra accumulated (Wilson, 2009). I assume the probability of exceeding IS_3 to be ≤ 0.1 based upon this assessment and the assumption that engineered bridges are less likely to be damage by tephra fall.

Rail transportation

Railway lines can be disrupted during tephra fall as a result of tephra covering tracks, reducing traction, jamming mechanical switches and disrupting communication signals. There have been few (three eruptions) documented examples of railway lines being impacted by tephra fall; the most recent was from the 2011 Shinmoedake eruption in Japan (see Magill et al., 2013). Of the documented instances, the majority are at IS_1 with an equal number at IS_0 and IS_2 (Figure 4.12A). The set of fragility functions derived from these data and expert judgment show that IS_1 has the highest probability of occurring for all tephra thicknesses (Figure 4.12B). This reflects the documented tephra fall impacts which are primarily loss of function and minor damage. Most railway tracks are between 100–180 mm high (Mundrey, 2010). If tephra at least this thick accumulates, the track will become buried and train wheels will no longer make contact with the track, causing complete disruption. This is reflected in the fragility function with a probability of equaling or exceeding IS_1 of 0.95 at 100 mm tephra thickness, i.e., a low probability (0.05) of sustaining no impact (Figure 4.12B). Tram tracks or tracks which are level with road surfaces (e.g., level crossings) are likely to be buried when thin tephra deposits accumulate (i.e., they may become disrupted with lower tephra fall intensities).

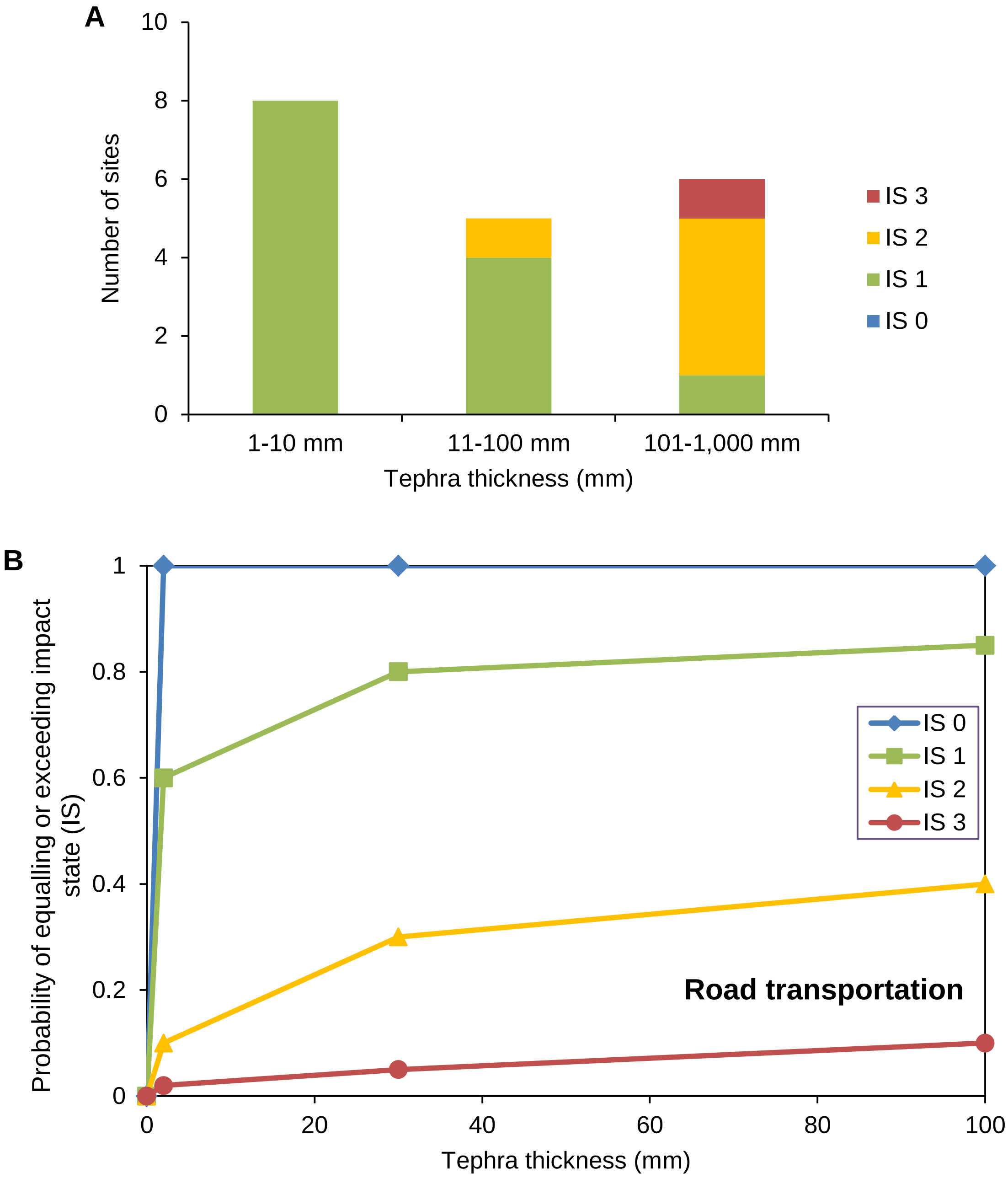


Figure 4.11: Road transportation: **A** histogram showing the number of available post-eruption impact data classified by IS for each tephra thickness bin; **B** set of fragility functions for road transportation showing probability of equalling or exceeding each IS for tephra thickness.

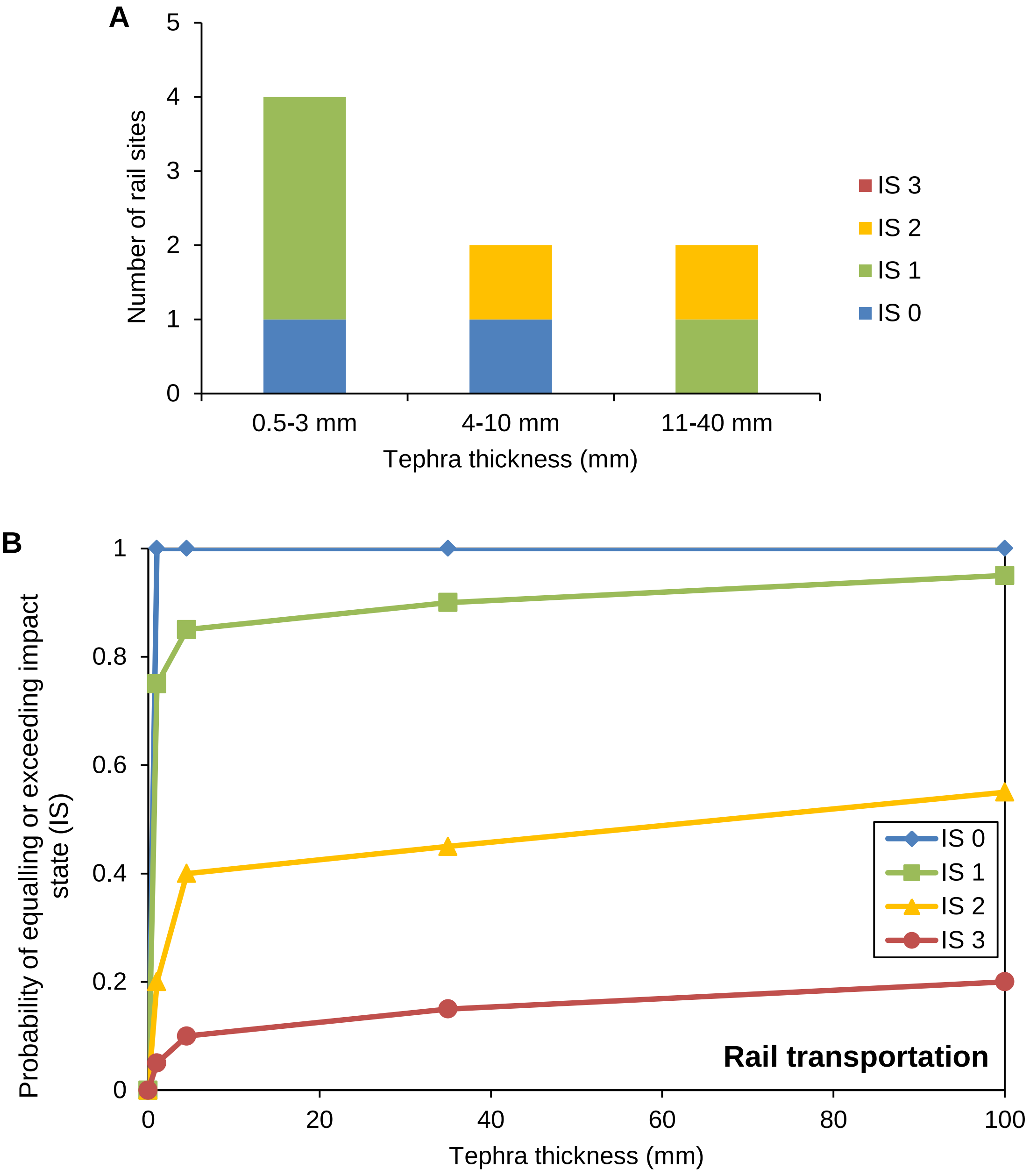


Figure 4.12: Rail transportation: **A** histogram showing the number of available post-eruption impact data classified by IS for each tephra thickness bin; **B** set of fragility functions for rail transportation showing probability of equalling or exceeding each IS for tephra thickness.

Airports

The most common impact to occur at airports during tephra fall is airport closure. Closure can result from tephra accumulating on runways and taxiways or the presence of tephra in the airspace surrounding an airport (not considered here). I am unaware of any instances of physical damage to runways or taxiways from direct tephra falls. However, at La Aurora International Airport, Guatemala, the runway was severely abraded after the 2010 eruption of Pacaya volcano as a result of tephra clean-up (Wardman et al., 2012a). Therefore, I only consider the probability that an airport will be closed (effectively IS_1) during tephra fall. Also the probability of closure is likely more useful to airport operators before and during an eruption than an estimate of potential damage.

Guffanti et al. (2008) catalogued impacts, primarily cause by tephra fall, to airports between 1944–2006. From this database, I extracted 44 instances where tephra thickness and airport status (open or closed) was recorded (Figure 4.13A), to calculate the probability of airport closure as a function of tephra thickness (Figure 4.13B). The resulting function shows that the probability of closure rapidly increases at low tephra fall intensities, up to 0.8 at 4 mm, and at 20 mm all airports examined here are closed. The main factors influencing airport closure are aircraft damage and life safety. Aircraft can sustain severe damage flying though tephra (Guffanti et al., 2010), therefore airports close (in most cases at relatively thin tephra deposits) to reduce the likelihood of damage and aircraft crashes. However, factors such as operational requirements, scheduling and economics, not accounted for here, may determine at which point an airport closes.

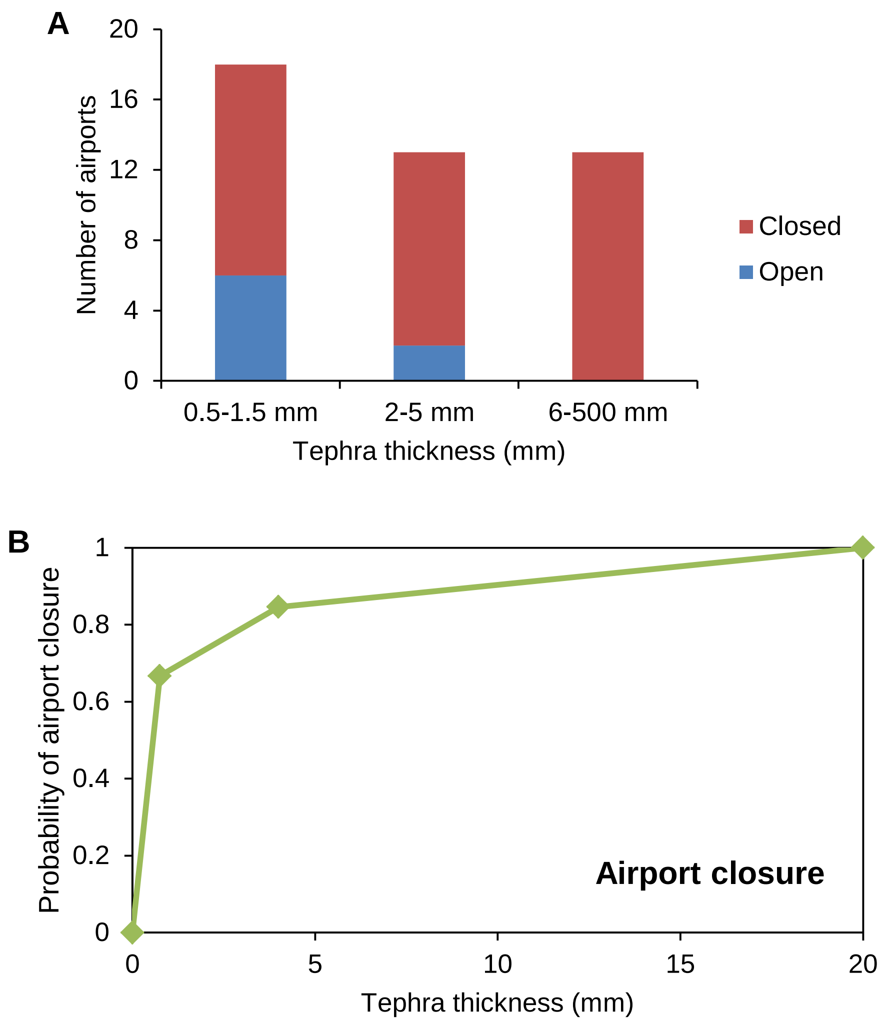


Figure 4.13: Airports: **A** histogram showing the number of airport status data available from post-eruption impact assessment for each tephra thickness bin; **B** fragility function showing the probability of airport closure as a function of tephra accumulation on the ground.

4.5.7 Critical components

Critical components such as heating, ventilation and air conditioning (HVAC) systems and small electronics (e.g., control systems, computers) are integral to most infrastructure sectors. Vulnerability data from post-eruption impact assessments (Figure 2.9B) and laboratory experiments (Gordon et al., 2005; Barnard, 2009; G. Wilson et al., 2012) indicate that these components are impacted by tephra fall. Common impacts are:

abrasion of fans and motors; blockage of filters and ventilation holes; decreased usability of computers; and temporary shutdown of systems. See Section 2.4.6 for further discussion of impacts to critical components.

While these vulnerability data document impacts, all impacts are measured against tephra thickness. However, tephra thickness is not the most appropriate HIM to use for these components, as the primary damaging mechanism is ingestion of tephra. As such, fragility functions for critical components are not derived here. Future experimental studies are required which consider the tephra concentration and the time components are exposure to tephra, i.e., experiments should match fragility to tephra ‘dose’. With this being said, an experimentally derived function which matches laptop computer functionality to tephra thickness is include in Appendix A, as a placeholder until future research is undertaken.

4.6 Summary

This chapter presents a structured framework for the quantitative assessment of infrastructure vulnerability to volcanic hazards, with a focus on the derivation of vulnerability and fragility functions for critical infrastructure. These functions provide quantitative estimates of impact intensity as a function of volcanic hazard intensity which are commonly desired for volcanic risk assessments. A standard framework promotes consistent vulnerability assessment and provides a method for the derivation of new fragility and vulnerability functions; a much needed step in volcanic risk assessment.

The framework details data source and preparation, function requirements, data fitting approaches, uncertainty considerations and documentation required to derive a new vulnerability and/or function for a critical infrastructure sector or component impacted by volcanic hazards. The primary data source used for volcanic vulnerability estimates are post-eruption impact assessments which document impacts from previous eruptions, summarised in Chapters 2 and 3. Laboratory experiments are beneficial as they can be repeated to generate large impact datasets. Experimental data are available for some infrastructure sectors and components; however, are limited due to the difficulties of replicating volcanic hazards and large infrastructure components in the laboratory. Where data are limited, expert judgment is used to estimate infrastructure fragility and vulnerability based on experts' knowledge of the impact(s) and hazard(s). A set of rules are devised to guide expert data fitting and to provide transparency of this process. Using these rules, expert derived functions are based on a standard foundation and are valid in a mathematical sense. These rules are not required for research fields where large datasets are typically available (e.g., earthquake vulnerability) and therefore are a unique approach for a field (volcanic vulnerability) with scarce vulnerability data.

Throughout the process of estimating fragilities and vulnerabilities, uncertainties related to raw data and its manipulation can affect the quality of the resulting functions. Where possible, all uncertainties should be reduced and documented. In addition, the derivation process, data preparation and assumptions should be documented to provide transparency of the process and allow other researchers to assess the quality and applicability of functions before use.

This chapter concludes with the derivation of fragility functions for discrete tephra fall impacts to the electricity supply, water supply, wastewater and transport networks (Section 4.5). I present these functions as an example of using the methodological framework (Section 4.4) to obtain new fragility functions. Data for the functions are primarily sourced from post-eruption impact assessments and supplemented by experimental data. Where data are limited or when fragility functions violated data fitting rules (e.g., decreasing impact with increasing thickness), expert judgment was used to modify functions using a transparent approach. The resulting functions give the probability of an infrastructure site being equal to or exceeding one of four impact states as a function of tephra thickness. These fragility functions represent the first attempt at quantifying the vulnerability of critical infrastructure sectors to tephra fall. As such, these functions should be used in volcanic risk assessments while considering all assumptions and limitations. When appropriate, these fragility functions should be updated with new post-eruption impact data, experimental data and expert judgment.

4.6.1 Where to next

The research field should adopt the method and framework present here as a standard approach to deriving and updating fragility and vulnerability functions for critical infrastructure sectors impacted by volcanic hazards. The derivation of fragility and vulnerability functions is the next step to contribute towards robust probabilistic volcanic risk assessments; essential for the successful management of volcanic risk.

In order to derive new, and update existing, fragility and vulnerability functions, high quality vulnerability data are required. Figure 4.14 shows that for the majority of the critical infrastructure considered here, data quality can be considered average (C) to below average (D). There are no infrastructure sectors that have vulnerability data which can be classified as high quality (A). This indicates that while there are data available to derive functions, additional research is required to increase data quality. A particular focus should be on the systematic collection of addition post-eruption impact data (Chapter 3) as this provides real-world vulnerability data. There also needs to be a continued focus on laboratory experiments to improve the understanding specific component vulnerabilities. The fragility functions presented here (Section 4.5) are based on currently available data and should be reviewed and updated when new vulnerability data becomes available. In the coming years I anticipate that the quality of vulnerability will increase across the board resulting in high quality functions for all critical infrastructure sectors.

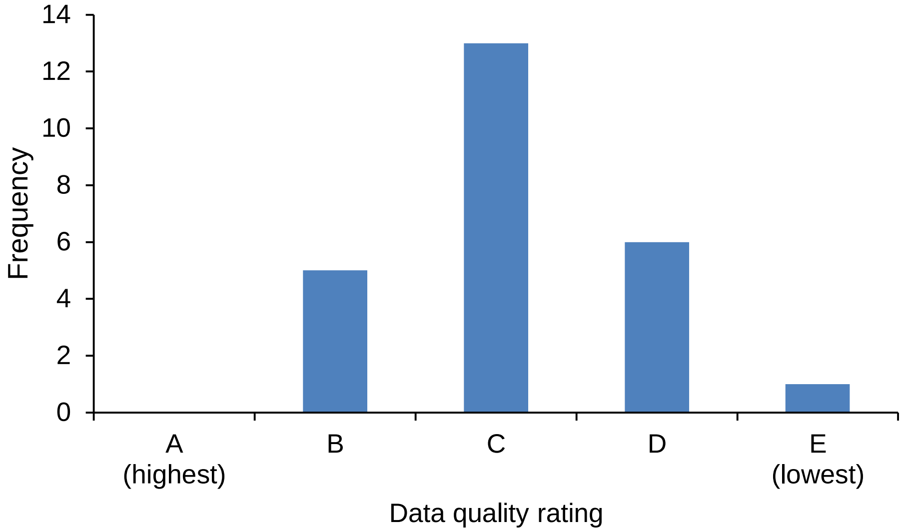


Figure 4.14: Quality rating of available vulnerability data for electrical supply, water supply, wastewater and transportation networks. Rating A is the highest quality and E is the lowest. See Table 4.2 for rating descriptions.

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Chapter Five – Probabilistic tephra hazard assessment for New Zealand

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Submitted: New Zealand Journal of Geology and Geophysics

Received: 9 March 2015

5.1 Abstract

We present a probabilistic tephra hazard assessment for the North Island of New Zealand using Monte Carlo methods and numerical tephra modelling. Eruptions were simulated from Mt. Taranaki, Mt. Ruapehu, Mayor Island, Tongariro, and the Okataina and Taupo Volcanic Centres using the advection-diffusion model TEPHRA2. For each volcanic source, simulated eruptions were grouped into eruption size classes and eruption parameters were stochastically sampled from statistical distributions based on values derived from recent eruption history studies. TEPHRA2 models important sedimentation processes, such as particle aggregation, and our simulations sampled a wider range of eruption sizes than considered by previous studies. Wind conditions, which influence tephra dispersal, were randomly selected from 15 years of available data (1999–2013). A catalogue of 25,000 simulated eruptions was produced with which

to estimate the tephra hazard at grid points across the North Island. For each location the hazard was estimated by summing the annual occurrence probability of each simulation which exceeded a given tephra thickness. The resulting hazard maps provide tephra thickness for the 500 and 2,500 year return periods. For both periods, the tephra hazard is highest immediately east of Mt. Ruapehu and Tongariro due to their higher eruption frequencies. Our hazard assessment can be used for volcanic risk assessments of exposed communities, buildings, infrastructure and land-use (e.g., agriculture and forestry) in New Zealand.

5.2 Introduction

Tephra is one of the most widespread volcanic hazards and while it does not usually cause fatalities, it can impact human health (Horwell and Baxter, 2006) and cause disruption and damage to buildings, infrastructure and agriculture leading to economic loss (Wilson et al., 2012). In proximal areas, thick tephra deposits can cause structural damage to buildings and burial of productive land, while in distal areas thin deposits of a few millimetres can disrupt the electrical network, close airports and reduce traction on roads (Wilson et al., 2014). As populations increase and move into more volcanically active areas, society will become more susceptible to impacts caused by volcanic eruptions (Chester et al., 2000).

Volcanic risk assessments, which comprise hazard, exposure and vulnerability assessments, establish and quantify which areas are at risk from volcanic eruptions (Wilson et al., 2014). These can lead to the development and implementation of mitigation actions to lower risk and minimise impacts. An integral part of risk assessment is the hazard assessment, which if insufficiently defined will lead to poor quality volcanic risk assessments. Tephra fall hazard assessments can consist of deterministic scenarios based on an eruption (or eruptions) which have been observed or mapped from the geological record (e.g., Johnston, 1997; Johnston et al., 1998; Marti et al., 2008). However, this can lead to an incomplete assessment as the whole range of possible eruption sizes and environmental conditions (e.g., winds), which combine to produce and disperse tephra fall, might not be preserved in the geological record (Bonadonna, 2006), or indeed have occurred yet. Using a combination of numerical tephra models with stochastic sampling techniques (e.g., Monte Carlo methods) allows large sets of eruption parameters and environmental conditions to be used, simulating a range of possible tephra dispersal scenarios. A probabilistic tephra hazard assessment combines all simulated outputs with eruption probabilities. Probabilistic assessments can quantify some uncertainty due to the large number of simulations used; however, they are still limited by the accuracy and relevance of the input data (Jenkins et al., 2012).

The North Island of New Zealand is a volcanically active region with a number of active or potentially active volcanoes capable of depositing tephra over large areas, depending on the eruption size and wind conditions at the time of eruption. Three previous studies (Magill et al., 2006; Hurst and Smith, 2010; Jenkins et al., 2012) have developed probabilistic tephra hazard assessments for multiple New Zealand volcanoes. All three use the ASHFALL dispersion model (Hurst 1994) in different methodological approaches. Magill et al. (2006) modelled probabilistic tephra hazard specifically for the Auckland region from six North Island volcanoes using relative probabilities of each volcano depositing tephra in the Auckland region. Hurst and Smith (2010) estimated the tephra hazard for the North Island from simulated eruptions from eight volcanoes. Eruption parameters and probabilities used were derived from eruption records, and in some cases (e.g., Mt. Ruapehu and Tongariro) were based on only a few data points. Jenkins et al. (2012) simulated eruptions from 11 volcanoes using eruption probabilities derived from global eruption databases to estimate the tephra hazard for urban areas with at least 400 residents/km^2, which equates to ~2% of the North Island's land cover (Newsome et al., 2013). There are a number of limitations in the selection of eruption parameters and the number of simulated eruptions for all models. As an example, Magill et al. (2006) only considered reference eruptions, not accounting for possible ranges of eruption parameters. Both Hurst and Smith (2010) and Jenkins et al. (2012)

simulated a different number of eruptions for each volcano and eruption size class. This may reduce the accuracy of the hazard output as for some volcanoes eruption parameters were randomly selected from a smaller sample pool than for other volcanoes. In addition to these models which consider multiple volcanoes, a number of studies have modelled tephra hazards from a single volcano (e.g., Dalziell, 1998; Bonadonna et al., 2005b; Bebbington et al., 2008; Jenkins et al., 2008) or modelled past eruptions (e.g., Hurst and Turner, 1999; Bonadonna et al., 2005a).

Here we provide a new comprehensive probabilistic tephra hazard model for the whole North Island of New Zealand that accounts for a wider range of eruption conditions and includes new eruption probability analysis. Using the numerical model TEPHRA2 (Bonadonna et al., 2005a), 25,000 eruptions are simulated from Mt. Taranaki, Mt. Ruapehu, Mayor Island, Okataina Volcanic Centre (OVC), Taupo Volcanic Centre (TVC) and Tongariro. Table 5.1 provides brief eruption history overviews of these six volcanoes. The Auckland Volcanic Field (AVF) is not included in this study because it is a volcanic field which makes future vent locations difficult to assess; we are only considering single vent volcanoes and caldera eruptions. We use Monte Carlo methods to generate eruption parameters from statistical distributions and to randomly sample wind profiles from real wind records for input into the model. We use a wider range of eruption sizes than previous studies, Volcanic Explosivity Index (VEI; Newhall and Self, 1982) 3–6 and up to VEI 7 for the TVC. This accounts for small tephra-producing eruptions not considered by Jenkins et al. (2012) and larger eruptions not considered by Hurst and Smith (2010). For some volcanoes, new eruption probabilities are derived from recent studies, such that Mt. Ruapehu and Tongariro have higher probabilities compared to Hurst and Smith (2010), and OVC is less active than in Jenkins et al. (2012). New tephra modelling techniques, after Biass et al. (2014) account for particle aggregation in the plume, which influences tephra sedimentation, and checks whether erupted mass is realistic given other eruption parameters.

Table 5.1: Summary of eruption histories for the study volcanoes.

Volcano	Classification	Description	References
Mt. Taranaki	Stratovolcano	Eruptive activity over the past ~115 ka. Defined by subplinian to Plinian eruptions interspersed with smaller explosive and effusive eruptions. Last confirmed eruption in 1755 CE.	Alloway et al. (1995); Shane (2005); Magill et al. (2006); Molloy et al. (2009); Turner et al. (2009).
Mt. Ruapehu	Stratovolcano	Four periods of cone building over past ~250 ka. Defined by hydrothermal to Plinian eruptions, largest producing an inferred 35 km high plume. Last eruption was a hydrothermal eruption in 2007 CE.	Graham and Hackett (1987); Cronin et al. (2003); Pardo (2012).
Mayor Island	Shield volcano	Volcanic activity over the past ~130 ka. Defined by lava flows, explosive eruptions and caldera collapse. Last eruption ~7,000 years ago which is one of only two Plinian tephra falls to reach the mainland.	Houghton et al. (1992); Wilson et al. (1995); Lowe et al. (2008); Molloy et al. (2009).
Okataina Volcanic Centre (OVC)	Caldera and domes	Early history is dominated by four periods of caldera collapse. Defined by effusive (lava domes) and explosive (Plinian eruptions) caldera infilling activity. The last eruption was the 1886 CE Tarawera basaltic Plinian eruption.	Nairn (2002); Smith et al. (2002); Houghton et al. (2004); Lowe et al. (2008); Cole et al. (2014).

Taupo Volcanic Centre (TVC)	Caldera and domes	Volcanic activity over the past ~300 ka. Early history defined by at least two caldera forming eruptions and since 26,000 years ago by explosive and limited effusive activity. The last eruption was ~1,800 years and was a large multi-phase Plinian eruption.	Cole et al. (1998); Wilson (1993); Wilson (2001); Mason et al. (2004); Wilson et al. (2009); Vandergoes et al. (2013).
Tongariro	Stratovolcano	Volcanic activity over the past ~340 ka. Early history defined by larger explosive cone building eruptions with smaller explosive and hydrothermal activity. Most recent eruption was two hydrothermal eruptions at Te Maari in 2012 CE.	Nairn et al. (1998); Moebis et al. (2011); Pardo et al. (2014).

This study provides a substantially improved tephra hazard assessment for North Island, New Zealand with which to determine estimates of tephra thickness at any point in the North Island for any return period of interest or conversely, estimates of the return period at any location for a given tephra thickness. These hazard outcomes can be used as the basis for volcanic risk assessment for exposed communities, buildings, infrastructure and agriculture.

5.3 Probabilistic modelling framework

The frequency and thickness of tephra fall at any location is dependent on eruption frequency and size, physical characteristics of tephra particles and wind conditions at the time of eruption. We use the advection-diffusion model TEPHRA2 (Bonadonna et al., 2005a) to simulate tephra fall extent and thickness across the North Island of New Zealand from six volcanoes: Mt. Taranaki, Mt. Ruapehu, Mayor Island, OVC, TVC and Tongariro. Each volcano had simulations corresponding to VEI 3–6. The TVC also included VEI 7 simulations. Each simulation outputs tephra accumulation as a mass per unit area, which we convert to thickness (millimetres) using a density of 1,000 kg/m^3 (Crosweller et al., 2012) for each point on a grid. Running the model a large number of times (e.g., 1,000 times) has two benefits: (1) the probability for exceeding certain tephra thickness thresholds can be estimated from the fixed number of simulations; and (2) overall aleatoric uncertainty is included in the output as a large number of eruption and environmental parameters are randomly sampled, accounting for natural variations in these parameters. By performing a sensitivity analysis varying the number of model simulations and wind profiles used, we determine the number of simulations required to obtain reproducible results (see Section 5.4.1). An essential input of tephra models is the eruption source parameters (e.g., column height, total grainsize distribution, erupted mass). These parameters are typically based on past eruptive activity with the assumption that future activity will be of a similar nature (Biass and Bonadonna, 2013). Using past eruption data, derived from geological investigations, reconstructions and eyewitness accounts, ensures realistic values are used, improving the accuracy of the model output. The following sections describe the input parameters (summarised in Table 5.2) and model implementation required to estimate the tephra hazard. Figure 5.1 shows the model workflow used.

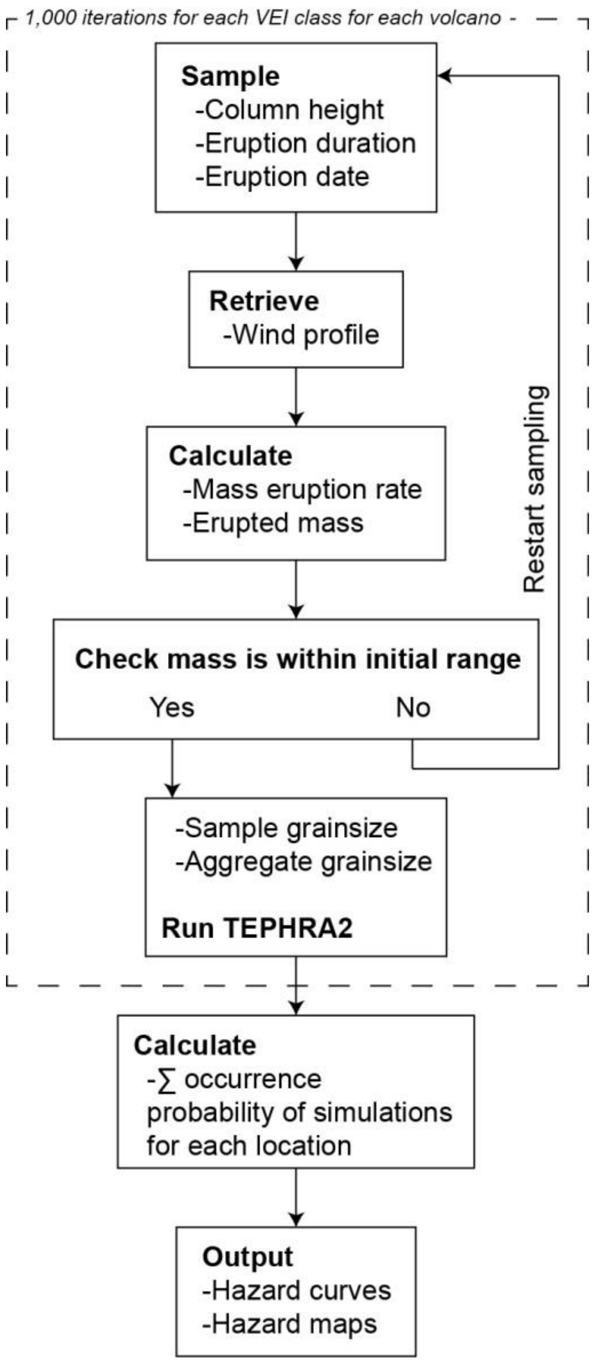

Figure 5.1: Tephra fall hazard assessment workflow. Sample indicates stochastic sampling of eruption parameters.

Table 5.2: Eruption parameters used as input values for the numerical model for each volcano. Values were based on eruption histories for each volcano, comparisons to similar volcanoes, where data were limited, and on the VEI classification system of Newhall and Self (1982). Grainsize distribution is expressed in phi units (Φ) where MdΦ is median phi and σΦ is standard deviation of phi.

Volcano	Plume height (km a.s.l.)[a]	Eruption duration (h)[b]	Erupted mass ($\times10^{11}$ kg)	MdΦ[c]	σΦ[c]	Grainsize range (Φ)	Aggregation coefficient[b]
Mt. Taranaki	10–40	0.5–6	0.05–300	-1.8–0.2	1–3	-8–10	0.2–0.8
Mt. Ruapehu	8.5–40	1–7	0.05–270	-1.8–0.2	1.4–3.4	-8–10	0.2–0.8
Mayor Island	10–40	0.5–6	0.05–300	-1–1	1–2	-8–10	0.2–0.8
OVC	10–40	2–6	0.1–300	-0.8–4	1–3	-7–10	0.2–0.8
TVC	10–40	0.5–7	0.1–1,200	-1.5–1.5	1–2	-3–10	0.2–0.8
Tongariro	10–40	0.5–6	0.05–270	-1–1	1–2	-7–10	0.2–0.8

[a] Logarithmic distribution, [b] Uniform distribution, [c] Gaussian distribution.

Table 5.3: Annual eruption probabilities for each volcano and probabilities for each VEI class conditional upon an eruption occurring.

Volcano	Annual eruption probability	Probabilities for each VEI class conditional upon an eruption occurring				
		VEI 3[d]	VEI 4	VEI 5	VEI 6	VEI 7
Mt. Taranaki	0.016[a]	0.15	0.07	0.02	4.8×10^{-3}	–
Mt. Ruapehu	0.28	0.15	0.09	0.03	6.2×10^{-3}	–
Mayor Island	1.1×10^{-4}	0.15	0.03	6.2×10^{-3}	2.0×10^{-3}	–
OVC	5.5×10^{-4} [b]	0.3	0.21	0.04	0.01	–
TVC	2.1×10^{-3}	0.15	0.08	0.04	0.01	4.8×10^{-3}
Tongariro	0.072[c]	0.15	0.09	0.03	6.2×10^{-3}	–

Data from Jenkins et al. (2012) except for: [a] Turner et al. (2009), [b] Wilson et al. (2009) [c] Scott and Potter (2014) and [d] this study.

5.3.1 TEPHRA2 model

TEPHRA2 is a model relying on an analytical solution of the advection-diffusion equations to describe tephra particle diffusion, advection and sedimentation (Bonadonna et al., 2005a). The model assumes a vertical plume extending above the vent from which the total erupted mass is released into the atmosphere for all grainsize classes. A value can be used to modify the mass distribution to take into account that the majority of the mass in an eruption column will be concentrated at the top. The atmosphere is divided into horizontal layers that are characterised by a uniform wind direction and velocity. At release points, located vertically within each horizontal layer and horizontally at (x,y) coordinates, all particles are released instantaneously and are assumed to be spherical with settling velocities which vary with the particle Reynolds number (Bonadonna et al., 2005a). Particles spread horizontally due to the effects of atmospheric diffusion and wind. Horizontal diffusion is considered isotropic (Bonadonna et al., 2005a) and is described in two regimes with the particle fall time threshold determining which is used. Coarse particles with low fall times follow linear diffusion based on the diffusion coefficient and fine particles follow a power law based on the apparent eddy diffusivity constant (Biass et al., 2014). Because the eruption column width increases with increasing height, particles become more spread out; this is accounted for by increasing the diffusion time as a function of column height (Connor and Connor, 2011). Particles travel (governed by particle density, grainsize, diffusion, gravity, atmospheric density) through the horizontal layer until they reach a lower layer where a different wind direction and velocity will influence sedimentation. This is an iterative process, and is repeated until the particles reach the ground. Once particles reach the ground, total tephra accumulation at each grid point is estimated as a mass per unit area. The reader is referred to Bonadonna et al. (2005a) for a detailed explanation of TEPHRA2.

5.3.2 Eruption probabilities

For this study we are calculating tephra dispersal from multiple volcanoes. As such, each point within the North Island might be impacted by eruptions from multiple volcanoes, each with their own eruption frequencies and size. Therefore the annual eruption probability of each volcano needs to be considered, as well as the probability of a specific eruption size conditional upon an eruption occurring (Table 5.3). Annual eruption probabilities used here are from Jenkins et al. (2012), who derived the values from the Smithsonian Institution volcano database (for volcanoes with extensive eruptive histories) and by averaging global probabilities based upon volcano classifications (for all other volcanoes). The annual eruption probabilities utilised for Mt. Taranaki, OVC, Mt. Ruapehu and Tongariro are based upon specific studies (Turner et al., 2009; Wilson et al., 2009; Scott and Potter, 2014) of their eruption histories rather than those of Jenkins et al. (2012). Using these new eruption probabilities based on eruption histories greatly improves the reliability of the hazard assessment. For example, Jenkins et al. (2012) used a return period of 8 years for OVC eruptions based on the entire eruption history recorded in the global eruption database (Siebert et al., 2010), whereas we use a return period of 1,800 years based on larger explosive eruptions in the eruption history, excluding small hydrothermal eruptions which will not contributed to tephra production.

Given an eruption at a particular volcano, the conditional probability that it is of a particular eruption size needs to be considered (Table 5.3). For eruption size classes VEI≥4 we use probabilities from Jenkins et al. (2012). Jenkins et al. (2012) derived conditional probabilities from the number of eruptions for each eruption size class recorded in the global eruption database (Siebert et al., 2010) for each volcano type classification (e.g., caldera, stratovolcano, shield). These conditional probabilities were verified against some well-studied volcanoes and assigned to volcanoes based upon their volcano type classification. We use this method to derive the conditional probability of VEI 3 eruptions, which were not directly evaluated by Jenkins et al.

(2012). The annual eruption probability and eruption size probability can be multiplied to give the annual probability of a particular eruption size from a particular volcano.

5.3.3 Eruption column height

Eruption column height is taken from the VEI classifications of Newhall and Self (1982) with adjustments made to lower and upper bounds to account for historic eruption data. For each eruption size class, the model randomly samples a value between the lower and upper boundaries on a logarithmic scale so that lower height columns have a greater probability of occurring than higher columns (Bonadonna et al., 2005a).

5.3.4 Mass eruption rate and erupted mass

The mass eruption rate (MER) is calculated from the column height and wind velocity at the tropopause, a height of ~11 km over New Zealand (Schofield et al., 2004), using the method of Degruyter and Bonadonna (2012). Erupted mass is then calculated using the MER and eruption duration. The resulting mass is compared to the initial range defined in Table 5.2 and if the calculated mass is within this range it is used in the model, if not a new column height and wind profile is chosen and the MER and mass are recalculated (Figure 5.1). This approach developed by Biass et al. (2014) prevents unrealistic eruption parameters being used in the tephra model.

5.3.5 Total grainsize distribution and aggregation

Total grainsize distribution (TGSD) is a critical input of tephra dispersal models. Here, all TGSDs are assumed Gaussian and generated from sets of medians and standard deviations stochastically sampled within predefined ranges for each volcano (Table 5.2). For simulated eruptions from Mt. Ruapehu, TVC and OVC, values were based upon past eruption grainsize distributions. Fewer data was available for the remaining volcanoes and therefore TGSDs from reported international literature (e.g., Girault et al., 2014) were used (Table 5.2).

Tephra particle aggregation influences particle transport and deposition which affects hazard estimation. Aggregation was taken into account using the method of Biass et al. (2014). This method removes an equal mass portion of particles from phi classes ≥4Φ and redistributes the mass evenly between classes -1Φ to 3Φ. The mass removed (the aggregation coefficient) for all volcanoes is randomly sampled between 20–80% (Table 5.2). This allows smaller particles to fall out as though they were larger particles (i.e., aggregates).

5.3.6 Wind profiles

Wind conditions during eruptions determine where tephra is deposited. For this study, 15 years (January 1999 to December 2013) of wind data were obtained from the National Centres for Environmental Protection (NCEP) and Atmospheric Research (NCAR) Reanalysis 1 database (Kalnay et al., 1996). This global database provides six hourly wind direction and velocity at 17 pressure levels on a 2.5° × 2.5° grid. We obtained wind data for a single point in central North Island to use for all volcanoes to provide consistency, because locally derived wind profiles for different locations vary in height due to different measurement techniques (NIWA, 2015).

Wind rose diagrams (Figure 5.2) for the 15 year dataset show that near the surface and at tropopause levels wind predominantly blows towards the east with velocity increasing with height. At higher elevations (~mid stratosphere) the wind blows towards the east and west, with wind towards the west more frequent. The frequency of wind direction changes throughout the year with wind typically blowing towards east throughout the southern hemisphere winter months (Figure 5.3). To account for wind direction variability through time, for each simulation of the model we randomly selected a wind profile from the 21,916 profiles available between 1999–2013.

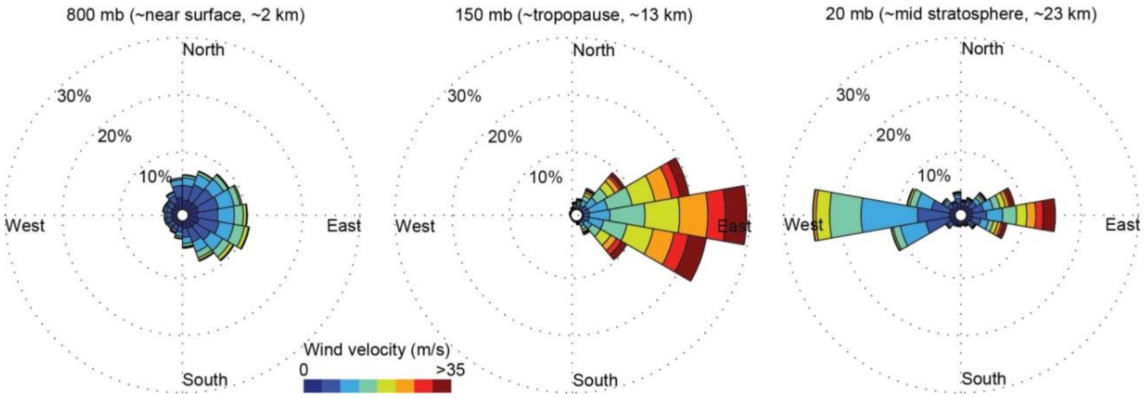

Figure 5.2: Wind rose diagrams showing variation in the direction wind is blowing towards and velocity for the North Island, New Zealand for the period 1999–2013 at three elevations: near surface (~2 km); tropopause (~13 km); and mid stratosphere (~23 km). Data source: NCEP/NCAR Reanalysis 1 database (Kalnay et al., 1996).

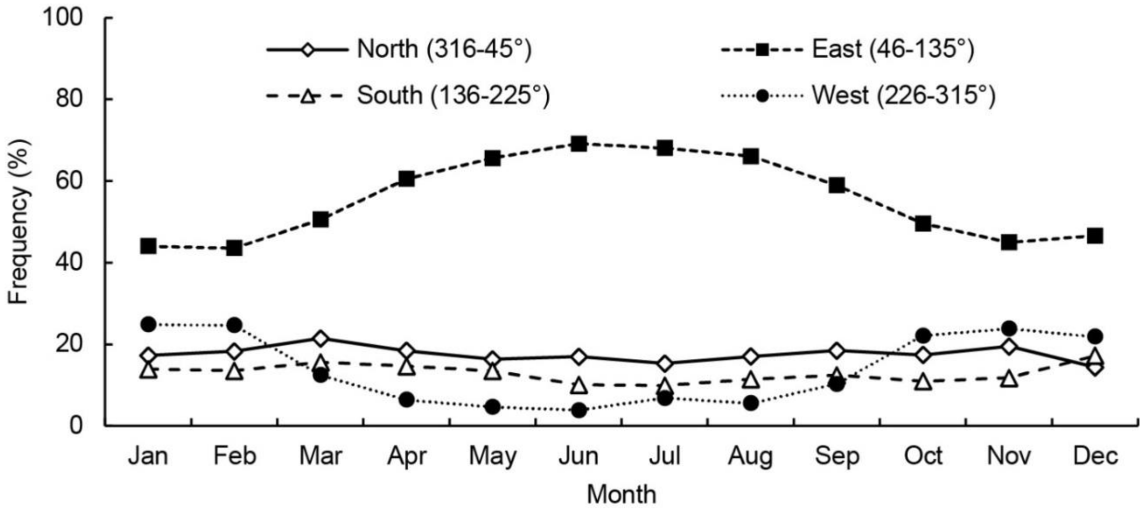

Figure 5.3: Monthly wind direction frequency from 1999 to 2013 for the North Island, New Zealand, for all elevations. Wind direction is defined as the direction it is blowing towards, measured in degrees clockwise from north. Symbols represent direction bins: open diamonds are north (316–45°), closed squares are east (46–135°), open triangles are south (136–225°) and closed circles are west (226–315°).

5.3.7 Model implementation

For each volcano, 1,000 model runs (see Section 5.4.1) of each VEI class were simulated using TEPHRA2, giving a total of 25,000 simulations of tephra thickness on a 5 km × 5 km grid across the North Island. At each grid location *x* the annual probability that the simulated tephra thickness *Z* exceeds a certain threshold *z* given volcano *V* erupts with VEI 3 can be calculated as:

$$P\left[Z \geq z | V_{erupt} | E_{VEI\ 3}\right]_x \approx \sum_{i=1}^{i=S} \left(\left(P\left[V_{erupt} | E_{VEI \geq 3}\right] \times w_{VEI\ 3} \right) / Total_S \right) \qquad (5.1)$$

where *S* is the number of simulations which produce tephra thicknesses exceeding a defined threshold *z* at grid location *x*, $E_{VEI \geq 3}$ is the probability of an eruption of VEI 3 or greater, $w_{VEI\ 3}$ is the weighting of VEI 3 eruptions from that volcano and $Total_S$ is the total number of simulations for that volcano. A VEI weighting is used because an equal number of eruptions for each VEI class is simulated, however each VEI class has a different probability of occurring (Table 5.3). The annual probability that a particular grid location will be impacted by tephra thicknesses exceeding a certain threshold from multiple volcanoes is calculated by summing the annual probabilities of all eruptions that reach that location and exceed the thickness threshold. Contemporaneous eruptions from multiple volcanoes affecting tephra accumulation at a grid location are possible, however we consider this negligible and do not include it here.

5.4 Results

5.4.1 Sensitivity analysis

A sensitivity analysis was undertaken to determine the variability and accuracy of the Monte Carlo technique used in this study. The analysis varied the number of model simulations and range of wind profiles used for each run to find a balance between model accuracy and computation time. The model was run for Mt. Ruapehu and calculated the probability of exceeding a tephra thickness of 0.1 mm at Auckland International Airport (260 km north of Mt. Ruapehu). Because this analysis did not depend on eruption frequency, an annual eruption probability was not used: the model was based on the assumption that the volcano had erupted. The number of simulations varied between 50–5,000 and subsets of wind profiles corresponding to 1, 3, 6, 12 and 15 years of data were used. Each combination of model simulations and wind subsets was performed 10 times to calculate means and standard deviations.

Results indicate the mean probability of exceedance (Figure 5.4A) and associated standard deviation (Figure 5.4B) change with different numbers of model simulations and wind profiles. With the minimum number of simulations there is a large spread of the mean exceedance probability for all wind datasets, however as the number of simulations increases the variability decreases and the mean and standard deviation stabilise for >500 simulations. With >1,000 simulations there is little difference between the different wind datasets, therefore we chose to use all available wind profiles (15 years), to account for the variability in wind conditions. The lowest standard deviation occurs when using 5,000 simulations, however performing this many simulations takes approximately four times longer than performing 1,000 simulations with only a 2% improvement in mean probability, so we use 1,000 simulations for each model run.

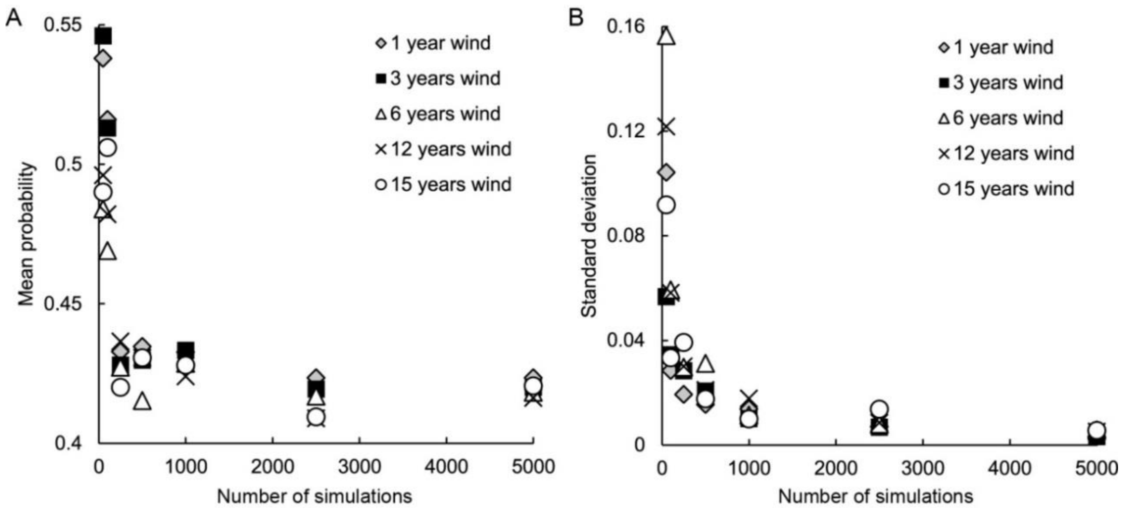

Figure 5.4: Sensitivity analysis for the Auckland International Airport receiving tephra from a simulated Mt. Ruapehu eruption. The number of simulations varied between 50–5,000 using five subsets of wind data given by different symbols. **A** shows the mean probability of exceeding 0.1 mm of tephra from 10 model iterations and **B**, the corresponding standard distribution.

5.4.2 Model outcomes

For each 5 km × 5 km grid point across the North Island, the tephra hazard was assessed using Equation (5.1) to sum the annual occurrence probability of all simulations from all volcanoes that reached that point and exceeded a particular tephra thickness. Continuous hazard curves were derived for each grid point by performing the calculation in Equation (5.1) using 500 tephra thickness thresholds distributed on a logarithmic scale from 0.1–10,000 mm. Figure 5.5 shows the mean return period for exceeding certain tephra thicknesses in one eruption at Auckland, Rotorua, Napier, New Plymouth and Wellington. By deriving continuous hazard curves for a range of tephra thicknesses the model can be used for any risk assessment and is not fixed to pre-defined thickness thresholds or return periods. Figures 5.6 and 5.7 show mean tephra thicknesses reached or exceeded from six volcanic sources for the 500 and 2,500 year return periods, respectively. These two return periods are used here as they are the two most common return periods used in natural hazard analysis and for building codes in New Zealand, especially for seismic loading (Standards New Zealand, 2004). Figure 5.8 shows mean tephra thickness exceedance for the 10,000 year return period. By fixing the tephra thickness at a particular threshold, the same hazard information can be displayed in a different way: Figures 5.9–5.10 show the mean return periods to exceed tephra thicknesses of 1 mm and 50 mm, respectively. At thicknesses of 1 mm airports may be disrupted, road markings start to be obscured and at 50 mm water pumps, non-structural building components and vehicles can be damaged (Wilson et al., 2014). Figure 5.11 shows return periods for exceeding 100 mm, a thickness where non-structural and light structural damage to buildings can occur.

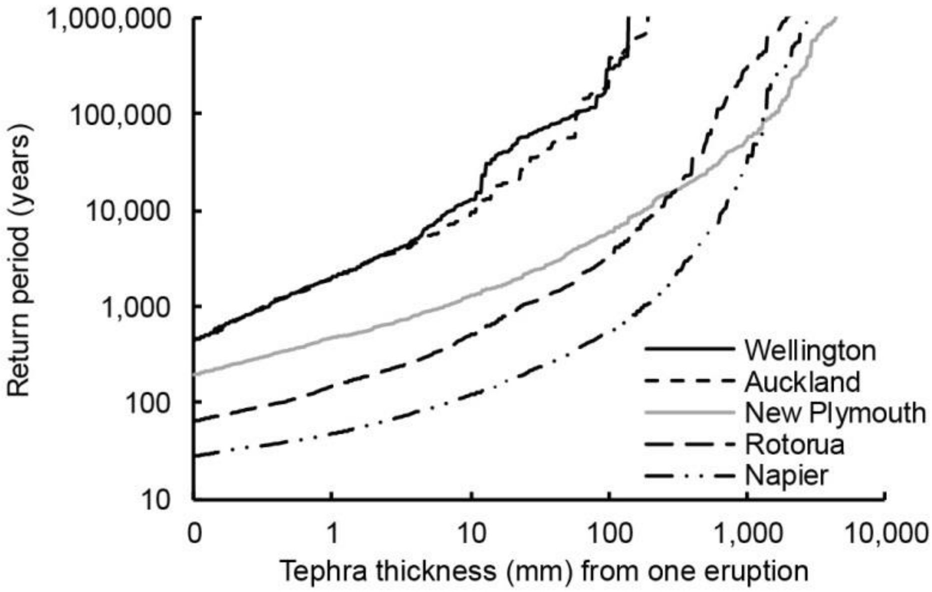

Figure 5.5: Hazard curves showing the mean return period (years) for exceeding certain tephra thicknesses at Wellington, Auckland, New Plymouth, Rotorua and Napier. Return period is the inverse of annual exceedance probability.

5.5 Discussion

Figure 5.6 shows that Mt. Ruapehu and Tongariro contribute the most to the tephra hazard in New Zealand as these are the two most active volcanoes. There are also minor contributions from Mt. Taranaki in the west and the TVC. When the return period is extended to 2,500 years (Figure 5.7), Mt. Ruapehu and Tongariro still provide the largest overall contributions, but there are slightly larger contributions from Mt. Taranaki and the TVC. As the return period is extended to 10,000 years the TVC begins to contribute more to the overall tephra hazard (Figure 5.8). Figure 5.9 shows that areas east of Mt. Ruapehu and Tongariro are likely to receive frequent (on human timescales; <100 years) thin tephra falls (1 mm) which may cause disruption to local communities and exposed assets (e.g., roads). Our tephra hazard is mostly consistent with Jenkins et al. (2012); however in their assessment there is a higher probability of receiving ≥1 mm of tephra on the east coast north of Gisborne due to the higher annual eruption probability they used for OVC eruptions.

In all hazard maps (Figures 5.6–5.11) it is evident that OVC and Mayor Island contribute very little to the overall North Island tephra hazard. This can be explained by the long return periods of eruptions from these two volcanoes which are ~2,000 years for the OVC and ~9,000 years from Mayor Island (Table 5.3). However, in the future these volcanoes, or any of the others, could change the tephra hazard for New Zealand if their eruption style, size or frequency changes. This highlights one of the limitations of probabilistic hazard assessments, which is that hazard maps show the mean tephra thicknesses to be exceeded in a given timeframe, however if an eruption occurs, particularly a large one, then greater tephra thicknesses could be experienced. End-users must keep this point in mind when using these probabilistic tephra hazard outputs.

The tephra hazard in New Zealand is highly dependent on the wind direction; seen in the tephra dispersal patterns shown on the hazard maps. Figures 5.6–5.11 show tephra dispersal towards the east, which is controlled by the predominant wind in the tropopause blowing in that direction (Figure 5.2). In addition to infrequent eruptions, another reason that there is minimal contribution of Mayor Island eruptions on the overall tephra hazard is due to the predominant wind direction. The majority of tephra erupted from Mayor Island is likely to be deposited into the ocean to the east of New Zealand, with tephra only being deposited on the mainland when there are unusual wind conditions. At least six tephra layers from previous Mayor Island eruptions have been found in ocean sediment cores located ~100 km northeast of Mayor Island (Shane et al., 2006).

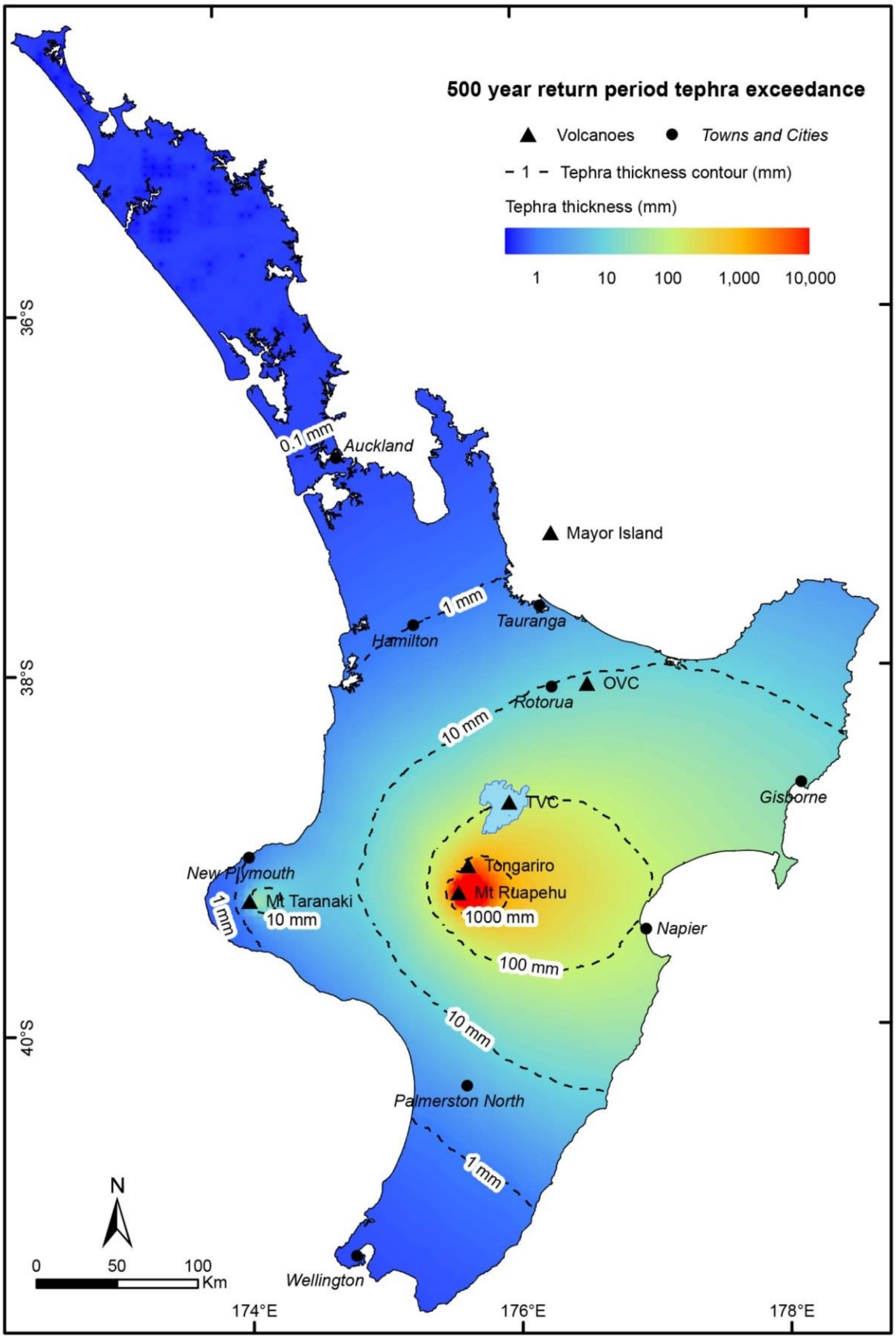

Figure 5.6: Probabilistic tephra hazard map showing mean tephra thicknesses (mm) exceeded for a 500 year return period from six volcanic sources. Main towns and cities indicated with circles and source volcanoes with triangles.

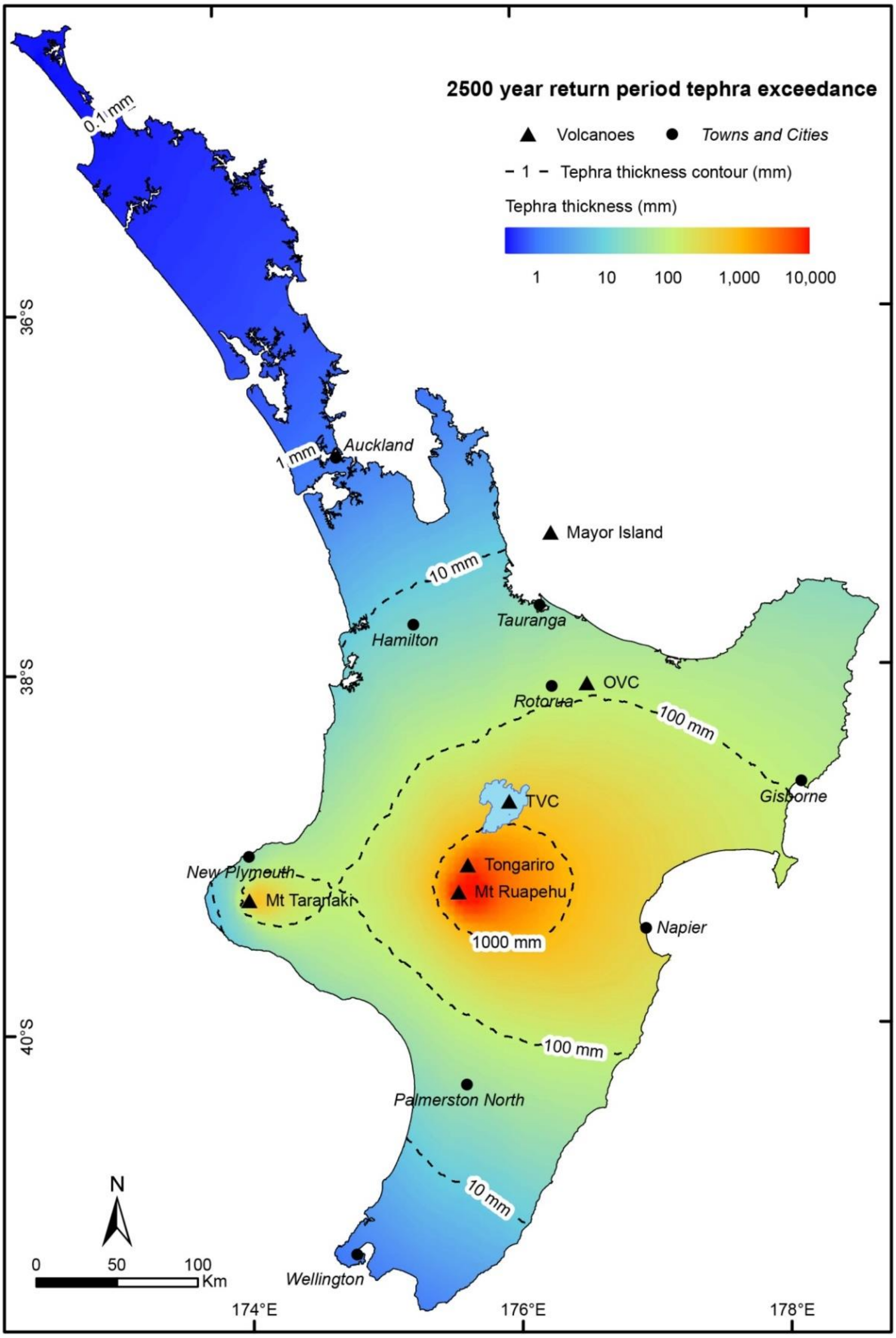

Figure 5.7: Probabilistic tephra hazard map showing mean tephra thicknesses (mm) exceeded for a 2,500 year return period from six volcanic sources. Main towns and cities indicated with circles and source volcanoes with triangles.

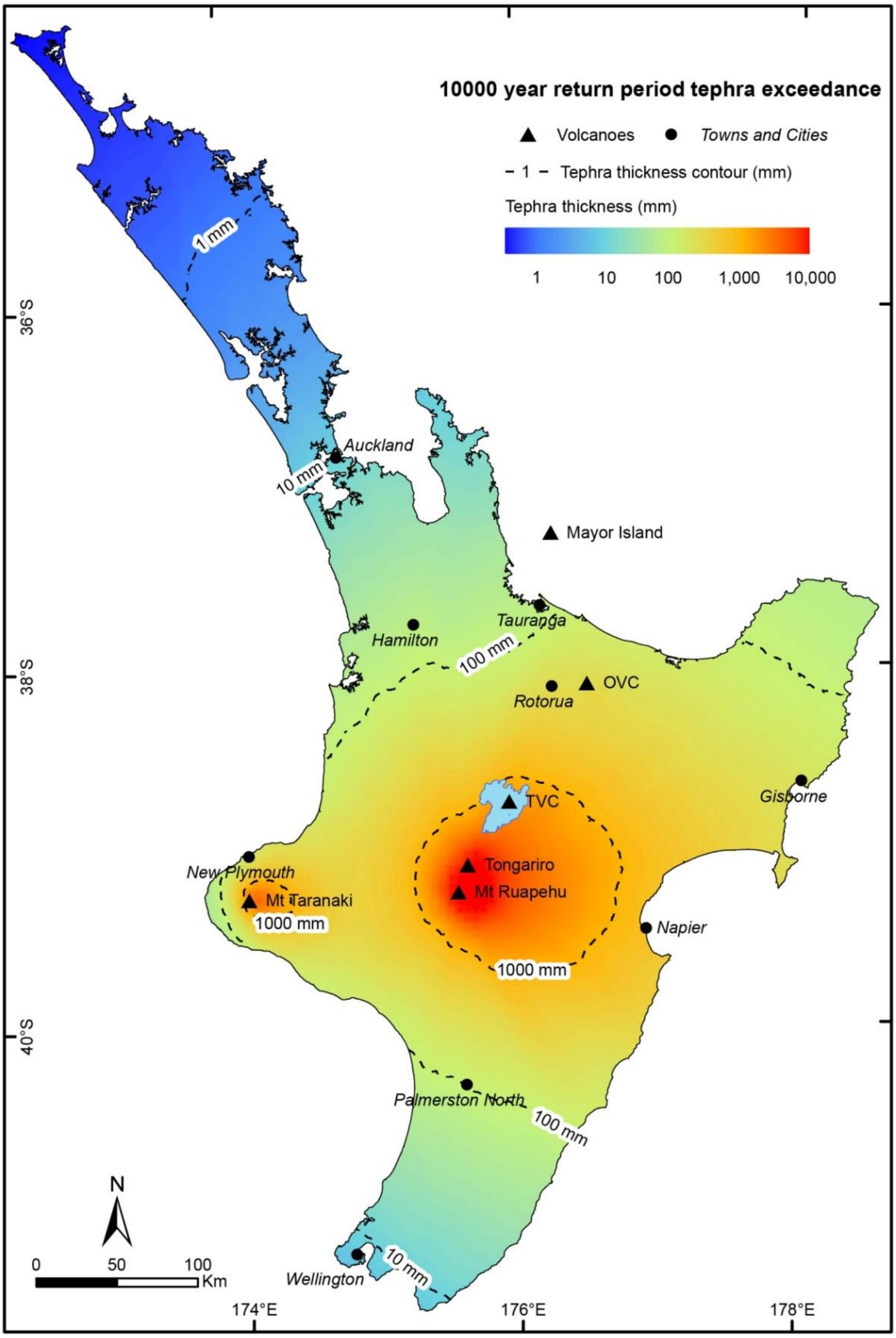

Figure 5.8: Probabilistic tephra hazard map showing mean tephra thicknesses (mm) exceeded for a 10,000 year return period from six volcanic sources. Main towns and cities indicated with circles and source volcanoes with triangles.

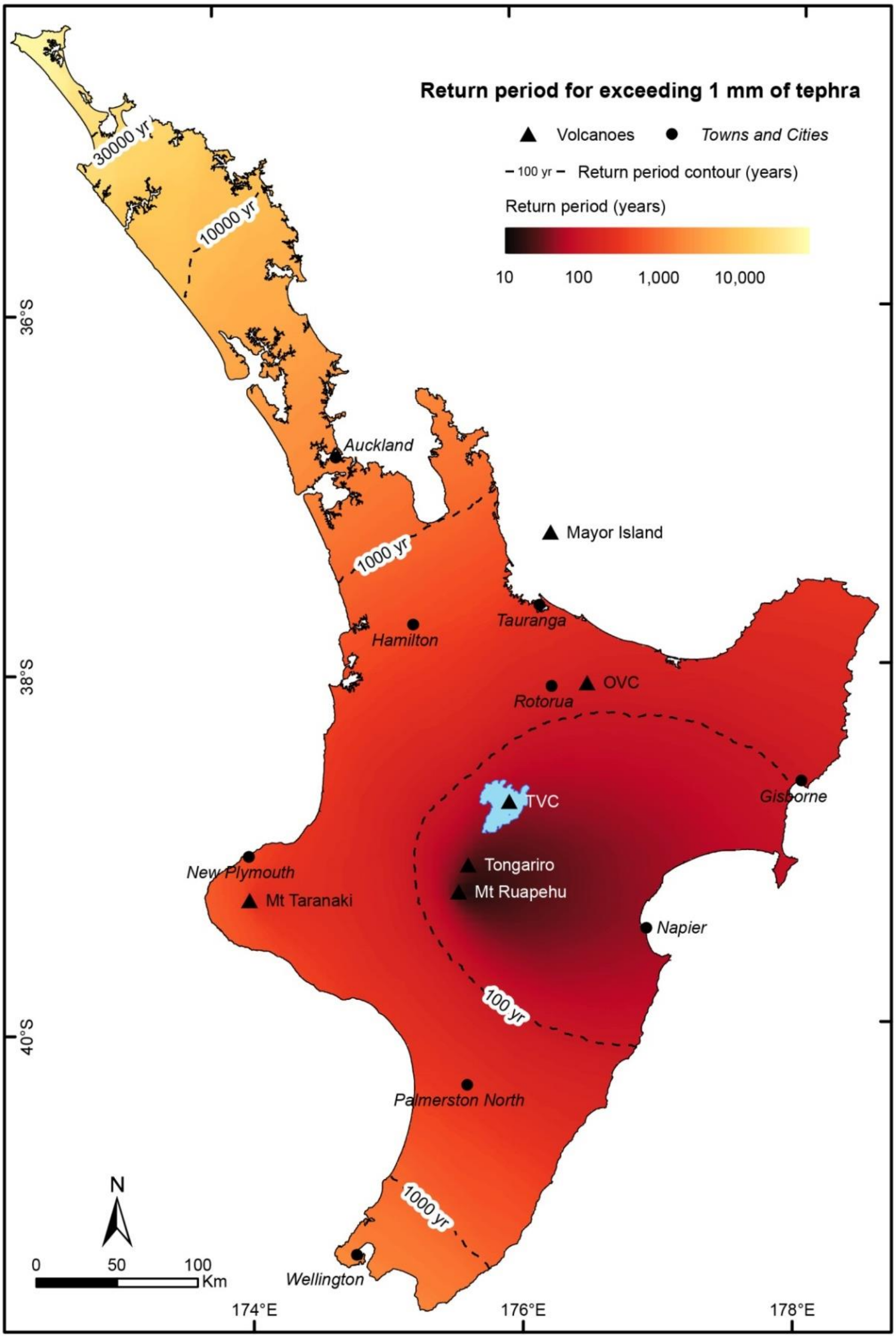

Figure 5.9: Probabilistic tephra hazard map showing mean return period (years) for exceeding 1 mm of tephra from six volcanic sources. Main towns and cities indicated with circles and source volcanoes with triangles.

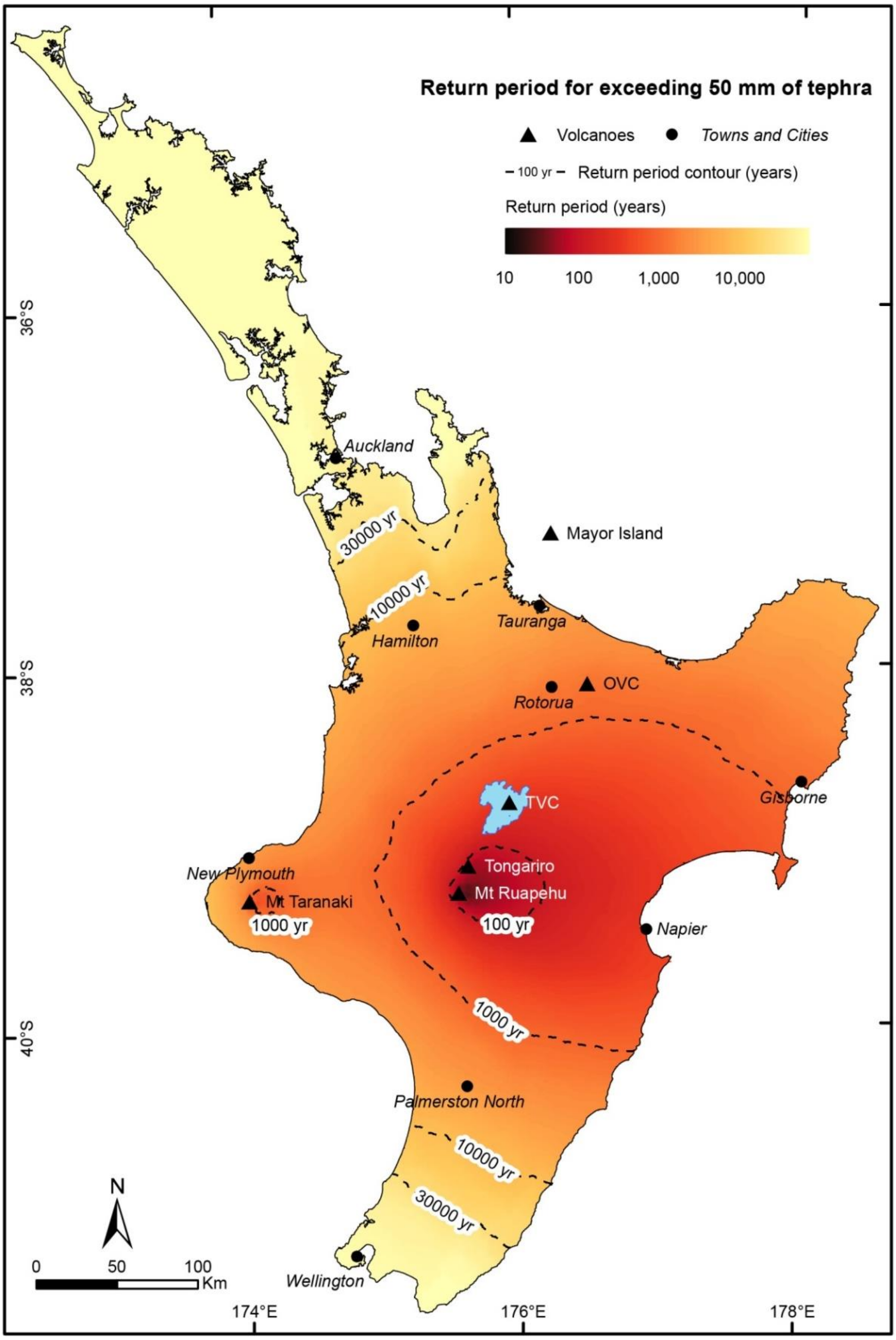

Figure 5.10: Probabilistic tephra hazard map showing mean return period (years) for exceeding 50 mm of tephra from six volcanic sources. Main towns and cities indicated with circles and source volcanoes with triangles.

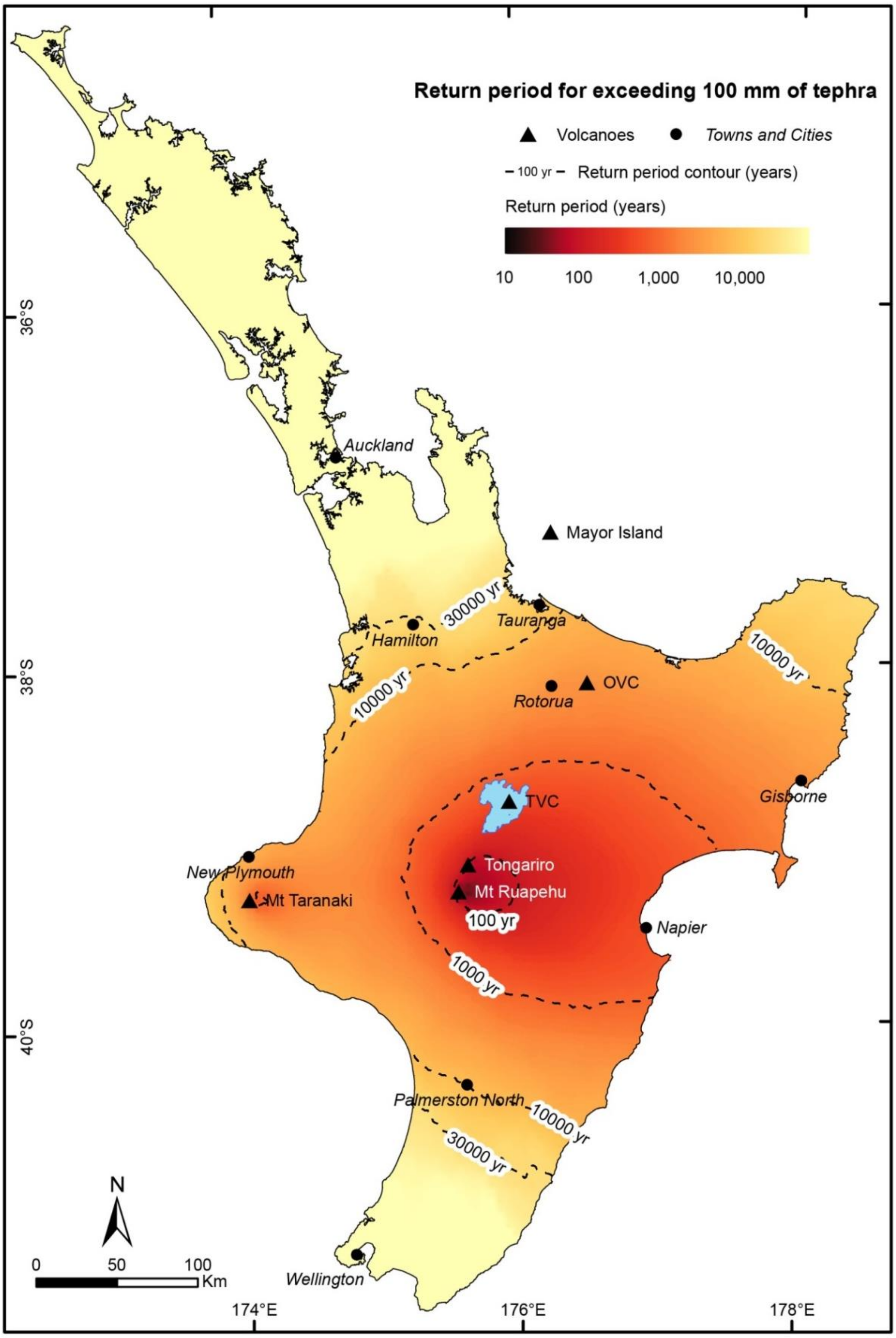

Figure 5.11: Probabilistic tephra hazard map showing mean return period (years) for exceeding 100 mm of tephra for six volcanic sources. Main towns and cities indicated with circles and source volcanoes with triangles.

Figure 5.5 also shows the influence of the wind direction on tephra dispersal and accumulation. Napier, located 120 km east of Mt. Ruapehu and Tongariro, has a smaller return period for a given tephra thickness than New Plymouth, located 26 km north of Mt. Taranaki, due to the predominant wind towards the east. For thicknesses <100 mm the mean return periods for the two locations differ by approximately one order of magnitude, however at 1,000 mm the curves intercept due to the less frequent large eruptions from Mt. Taranaki depositing tephra on New Plymouth. In addition, Figure 5.5 shows generally that Auckland (New Zealand's largest city) and Wellington (New Zealand's capital city) are expected to receive considerably less tephra than central North Island locations. This can be explained by their distance from the active volcanoes and their locations, which are infrequently downwind from the central North Island volcanoes (Figure 5.2). Tephra has been deposited in Auckland in the past, most recently during the 17 June 1996 eruption of Mt. Ruapehu. While this was a relatively small eruption (VEI 3), <1 mm of tephra was deposited at Auckland International Airport (260 km north of the vent) resulting in its closure (Johnston et al., 2000).

5.5.1 Comparison with existing models

Magill et al. (2006), Hurst and Smith (2010) and Jenkins et al. (2012) developed probabilistic tephra models for New Zealand. Due to the different methodologies and hazard models used (these previous studies used the ASHFALL model), there are differences in the hazard outcome between the models. While both TEPHRA2 and ASHFALL are based on the equations and principles of Macedonio et al. (1988), there are some differences between these models. Each model treats diffusion of particles through the atmosphere differently, with TEPHRA2 using two diffusion laws for different particles (Bonadonna et al., 2005a), while ASHFALL applies a horizontal corrective term once a particle reaches the ground based on its fall time (Hurst, 1994). Another difference between the models is the treatment of particle grainsize distributions. ASHFALL uses particle settling velocities and therefore does not discriminate between coarse and fine particles or require a Gaussian distribution (Hurst, 1994), whereas TEPHRA2 uses a Gaussian distribution in phi classes (Bonadonna et al., 2005a).

The study of Magill et al. (2006) is not directly comparable because they use relative probabilities of eruptions from different volcanoes reaching the Auckland region and not annual eruption probabilities. For the most part, our model is similar to that of Jenkins et al. (2012) because similar eruption probabilities were used for all volcanoes except the OVC. For the OVC we used a lower eruption probability, based on the eruption history, and therefore in our model this volcano contributes less to the overall tephra hazard than it does in the Jenkins et al. (2012) model. Compared to Hurst and Smith (2010), our model has a larger hazard footprint for both the 500 (Figure 5.6) and 10,000 year (Figure 5.8) return periods, especially in the central North Island. One possible reason for this is that our model used annual eruption probabilities for Mt. Ruapehu and Tongariro 1–2 orders of magnitude larger than those of Hurst and Smith (2010), who derived them from six eruptions in the last 15,000 years. The probabilities we used for these two volcanoes were derived from new eruption history studies that suggest these volcanoes are more active than Hurst and Smith (2010) calculated. Because these eruption probabilities are higher, these volcanoes will contribute more to the overall tephra hazard. The difference between hazard outcomes is less pronounced at thin tephra thicknesses further away from the volcanic sources.

In addition, differences between the hazard outcomes could be due to model implementation. Hurst and Smith (2010) implemented different maximum volume constraints for each volcano. These limits were derived from eruption histories and expected theoretical maximum eruption sizes. This does however ignore the very low occurrence probability of larger eruptions from any of the volcanoes. Our model imposes higher maximum sizes than Hurst and Smith (2010) for all volcanoes except the TVC. Because these larger eruptions are unlikely, they have low associated occurrence probabilities (Table 5.3), however are still included as potential large sources of large tephra deposits.

For each VEI class, we simulated an equal number (1,000) of eruptions and took the proportion of each of these into account using a weighting value (see Section 5.3.7 and Equation 5.1), whereas Hurst and Smith (2010) simulated an uneven number of eruptions for each volcano and Jenkins et al. (2012) simulated an uneven number of eruptions for each VEI class. Simulating an uneven number of eruptions directly accounts for the different frequencies of different eruption sizes; however, it also reduces the variability in the random sampling of wind conditions and eruption parameters. For example, our model simulated 1,000 VEI 7 eruptions from Taupo, whereas Jenkins et al. (2012) simulated ~33 eruptions which could result in variability in hazard outcomes as a result of the smaller sample size (see Section 5.4.1 and Figure 5.4).

Despite these differences, no one model is more correct than another, as all models approximate natural processes in mathematical and physical frameworks. This, however, does highlight that different hazard outcomes are produced depending on the modelling approach used, its implementation and the input of eruption source parameters. Our tephra hazard assessment is an improvement on existing assessments due to improved modelling techniques which include particle aggregation, eruption parameter validation, a wider range of eruption magnitudes and new eruption probabilities.

5.5.2 Model limitations

There are limitations with our modelling approach primarily related to eruption probabilities and input parameters. For this assessment we used eruption probabilities from Jenkins et al. (2012) which have been derived from global eruption databases. Jenkins et al. (2012)’s probabilities contain some uncertainty due to varying data completeness, however using these probabilities allowed for consistent coverage for all volcanoes. Where there were inconsistencies with eruption frequency and style we substituted more realistic values. For example, the recent history of the OVC is dominated by small hydrothermal eruptions in lakes and craters around the margin of the caldera which produce very small, if any, tephra (Siebert et al., 2010; the 1886 CE Mt. Tarawera eruption notwithstanding). Because these eruptions will not contribute to the tephra hazard, they are not considered in assessing eruption frequency in this study and as a result the eruption return period increases from 8 years (Jenkins et al., 2012) to 1,800 years (Wilson et al., 2009).

To reduce complexity within our model we have not included the time-variability of eruption probabilities, nor the possibility of clustered eruptions or eruptive episodes. Instead we assign constant annual eruption probabilities to each volcano. Clustered eruptions and eruptive episodes will likely change the hazard outcome and should be included in future tephra hazard assessments.

For the volcanic sources used here there are discrepancies in terms of knowledge about eruption histories, due to eruption frequency and the number of detailed studies undertaken for each source. To account for this discrepancy we use the VEI classification scheme to define ranges of plume height and erupted mass for each VEI class. This may result in uncertainty as some volcanoes may not produce eruptions that occupy the entire range of input values. Grainsize distribution is a critical model input which influences tephra dispersal, however for some we use distributions based on international literature, as typical total grainsize distributions for these volcanoes have not been identified from past eruptions. Uncertainties within eruption input parameters can lead to uncertainties within tephra hazard outputs and therefore should be refined in further studies.

Another factor influencing tephra dispersal is wind direction and speed. Here, we use wind profiles from one location in the Central North Island for all volcanoes. Using this approach assumes that wind conditions across the whole North Island are the same, which may be an over simplification. However, this approach provides consistent height and temporal coverage for each volcano. In addition, TEPHRA2 does not account for changes in wind conditions spatially away from the volcanic source, unlike other more complex 3D models (e.g., FALL3D, HYSPLIT, NAME). We also assume that wind conditions of the past 15 years will be the same in the future, which may not necessarily be the case given possible effects of future climate change.

Another limitation is that the Auckland Volcanic Field (AVF) is not included in this hazard assessment because it is a volcanic field which makes future vent locations difficult to assess, and we were only considering single vent locations and caldera eruptions. In addition, a number of past AVF eruptions are less than our minimum eruption magnitude value of VEI 3 (Kereszturi et al., 2013) and will not contribute to the North Island-wide tephra hazard. However, tephra from eruptions in the AVF will cause impacts to local infrastructure as tephra deposits in excess of 1 mm have been identified several to tens of kilometres away from the source AVF vent (Kermode, 1992). AVF eruptions were included by Hurst and Smith (2010) and should be included in further iterations of probabilistic tephra modelling.

5.6 Conclusions

In this study we present a probabilistic tephra hazard assessment for the North Island of New Zealand using the advection-diffusion model TEPHRA2. The volcanic sources used are: Mt. Taranaki; Mt. Ruapehu; Mayor Island; Tongariro; and the Okataina and Taupo Volcanic Centres. For each volcano, 4,000 simulated eruptions were performed for VEI 3–6 with the addition of 1,000 VEI 7 simulations for the TVC. Eruption source parameters for these simulations were based on eruption histories and those defined by the VEI classification system, with values for each randomly sampled from statistical distributions. For each simulation a wind profile was randomly selected from a database containing profiles spanning 1999 to 2013; this accounts for the influence wind has on tephra dispersal.

The tephra hazard at each grid point (5 km × 5 km) in the North Island was estimated by summing the annual occurrence probability of each simulation which exceeded a given tephra thickness and which reached that location. Eruption probabilities are the largest source of uncertainty in our model (in addition to uncertainties inherent within TEPHRA2) and our model accuracy will improve with further research refining these probabilities. However, our model is an improvement upon exiting models as we used updated eruption probabilities from new eruption history studies for some of the volcanoes. Results of the tephra fall hazard assessment are presented in three ways: (1) hazard maps with fixed return periods, which spatially show varying mean tephra thickness; (2) hazard maps with fixed tephra thickness threshold, which spatially show varying mean return periods; and (3) hazard curves for select locations, which show mean return period as a continuous function of tephra thickness. Presenting the hazard outcomes in these different ways allows end-users to select the most appropriate end product for their needs. These products can feed into probabilistic risk assessments for exposed communities, buildings, infrastructure and agriculture across the North Island.

The results of the hazard assessment show that the highest tephra hazard is immediately east of Mt. Ruapehu and Tongariro. This pattern results from two factors: (1) these two volcanoes are the most active and have the highest annual eruption probabilities of the study volcanoes; and (2) the wind across the North Island predominantly blows towards the east, transporting erupted tephra in this direction. As the return period is increased, other less active volcanoes (e.g., Mt. Taranaki and the TVC) begin to contribute to the tephra hazard. Compared to previous models our assessment has a larger tephra hazard footprint due to improved eruption probability values and the inclusion of a larger range of eruption magnitudes. This means that more assets (infrastructure, buildings and agriculture) are exposed to potential tephra which requires reassessment of risk estimates and management strategies.

5.7 Acknowledgments

This work was initiated as part of the Specialisation Certificate in Geological and Climate Related Risk (CERG-C) at the University of Geneva, Switzerland. We gratefully acknowledge funding support from DEVORA (GW, TW, NID), the Ministry of Business, Innovation and Employment's Natural Hazard Research Platform contract C05X0804, GNS Science, Royal Society of New Zealand (Canterbury Branch) travel grant (GW) and the Mason Trust (GW).

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Chapter Six – Volcanic tephra fall risk assessment for New Zealand's electrical transmission network

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Intended submission for: Bulletin of Volcanology

6.1 Abstract

This study presents a volcanic tephra fall risk assessment of the electrical transmission network in the North Island of New Zealand. Electrical assets considered are generation sites (hydroelectric, thermal and geothermal power stations), substations and transmission lines. Fragility functions expressing the probability of electrical assets being at one of four impact states as a function of tephra thickness are derived for each asset class. Functions are derived using data from post-eruption impact assessments, expert judgement and laboratory experiments. Using a probabilistic tephra fall model, we obtained tephra thickness exceedance for 500 and 2,500 year return periods for all electrical infrastructure locations in the North Island. Modelled tephra thickness and fragility functions are used to estimate impact state exceedance for 500 and 2,500 year return periods by randomly generating impact states based on the relative probability of occurrence for each asset. Our risk assessment shows the highest risk to the transmission lines is immediately to the east of Mt. Ruapehu and Tongariro due to their high eruption frequency and the predominant wind direction towards the east. In this

area the probability of disruption of the circuit resulting from insulator flashover is ≥0.8 for both return periods and subsequently the highest priority area for mitigation implementation. Substations and generation sites to the north and east of Mt. Ruapehu will likely sustain impacts requiring extensive repair and/or replacement of components causing disruption (highest impact state) for both return periods. Our methodology can be used as a near real-time predictive impact assessment tool to assess impacts during a volcanic eruption as well as in broad risk assessment tools such as RiskScape.

6.2 Introduction

Electricity is one of the most critical infrastructure services in society as it is widely relied upon by other infrastructure sectors for their continued operation (Bose, 2005). Continued function of the electrical transmission network is critical during natural hazard impacts, including volcanic eruptions, to maintain economic activities in unaffected areas and for response activities (Wardman et al., 2012).

Tephra fall is the most widespread volcanic hazard and typically causes disruption and damage to electrical transmission networks (Wardman et al., 2012; Wilson et al., 2012). The most common impact on the transmission network (typically ≥110 kV) is insulator flashover. This occurs when tephra accumulates on insulators in the presence of moisture, thereby increasing their conductivity which can lead to an unintended electrical discharge over the surface of the insulator (a flashover) (Wardman et al., 2012). If the flashover current is high enough to trip circuit breakers, disruption of transmission on that circuit will occur and damage to components may result. Another common impact is the abrasion of turbines at hydroelectric power stations (HEP), as tephra suspended in reservoirs settles and passes through the station and turbines. Abrasion damage to turbines or cooling systems at thermal or geothermal stations, or the fear of such damage, may require complete or partial shutdown (G. Wilson et al., 2014). Table 6.1 and Section 6.4 summarise damage and disruption commonly observed for electrical transmission networks.

Table 6.1: Summary of commonly observed and likely tephra fall impacts on electrical transmission networks in terms of physical damage and loss of functionality (summarised from Wardman et al., 2012; G. Wilson et al., 2014).

Asset	Sub-sector	Vulnerable components	Observed and likely physical damage	Observed and likely reduction in service delivery
Generation sites	General	Equipment buildings, generator halls, offices, and electrical equipment support structures. Electronic and mechanical control systems. Exposed motors. Transformers.	Non-structural and structural damage to buildings and structures.	Ingress of tephra into buildings and sensitive electronics and mechanical components, reducing their operability. Shutdown for cleaning, repair or to prevent further damage.
	Hydroelectric power (HEP)	HEP turbines and intake gates. Storage reservoir.	Abrasion of HEP turbine blades, intake gates and other metal components from suspended tephra.	Deposition of tephra into storage reservoirs, reducing storage volume and capacity to generate electricity.
	Thermal power	Air intakes (including filters) for combustion. Cooling systems. Fuel supplies.	Abrasion and jamming cooling systems including upward facing fan blades. Abrasion of heat exchangers in cooling systems.	Blockage of air intake filters, affecting combustion process. Blockage of heat exchangers in cooling systems. Contamination of fuel supply. Contamination of intake water.

Asset	Sub-sector	Vulnerable components	Observed and likely physical damage	Observed and likely reduction in service delivery
	Geothermal power	Well heads. Pipe networks. Cooling systems.	Abrasion and jamming of upward facing fan blades in cooling systems. Abrasion and damage to well heads. Possible damage to over ground pipe network.	Blockage of heat exchangers in cooling systems. Blockage of cooling system fans. Contamination of intake water.
Substations		Control and switching equipment and components. Gravel ground cover. Insulators. Transformers. Buildings and structures.	Damage to buildings and structures. Abrasion and jamming of mechanical components. Overheating of equipment causing permanent damage.	Shutdown for cleaning and repair. Contamination of gravel ground cover requiring cleaning. Ingress of tephra into buildings and sensitive electronics and mechanical components, reducing their operability.
Transmission lines		Insulators. Conductors (lines). Support structures.	Breakage of lines or support structures. Etching or abrasion of insulator surfaces.	Insulator flashover causing disruption of transmission on line (circuit). Disruption of transmission on line for cleaning or repair.

The high voltage (HV) electrical transmission and generation network in the North Island, New Zealand is an expansive system stretching the length of the island and comprising thousands of components (Figure 6.1). Due to active volcanism in the North Island, the transmission network has the potential to be impacted by tephra fall. Determining the areas of the network most at risk from tephra fall impacts is paramount to successful volcanic risk management and risk reduction. In this study, we use a probabilistic tephra fall model for six volcanoes in the North Island, developed in Chapter 5, to establish the tephra fall hazard at electrical infrastructure sites (Section 6.3). To assess vulnerability, we derive volcanic fragility functions for generation sites, substations and transmission lines which give the probability of exceeding one of four impact states as a function of tephra thickness (Section 6.4.1). Combining the hazard and vulnerability assessments (Section 6.4.2), we assess the risk to the HV electrical transmission network in the North Island for hazard return periods of 500 and 2,500 years (Sections 6.5–6.6). We also show the application of our vulnerability assessment during a volcanic eruption by using three eruptions from Mt. Ruapehu eruptions (Section 6.6.1).

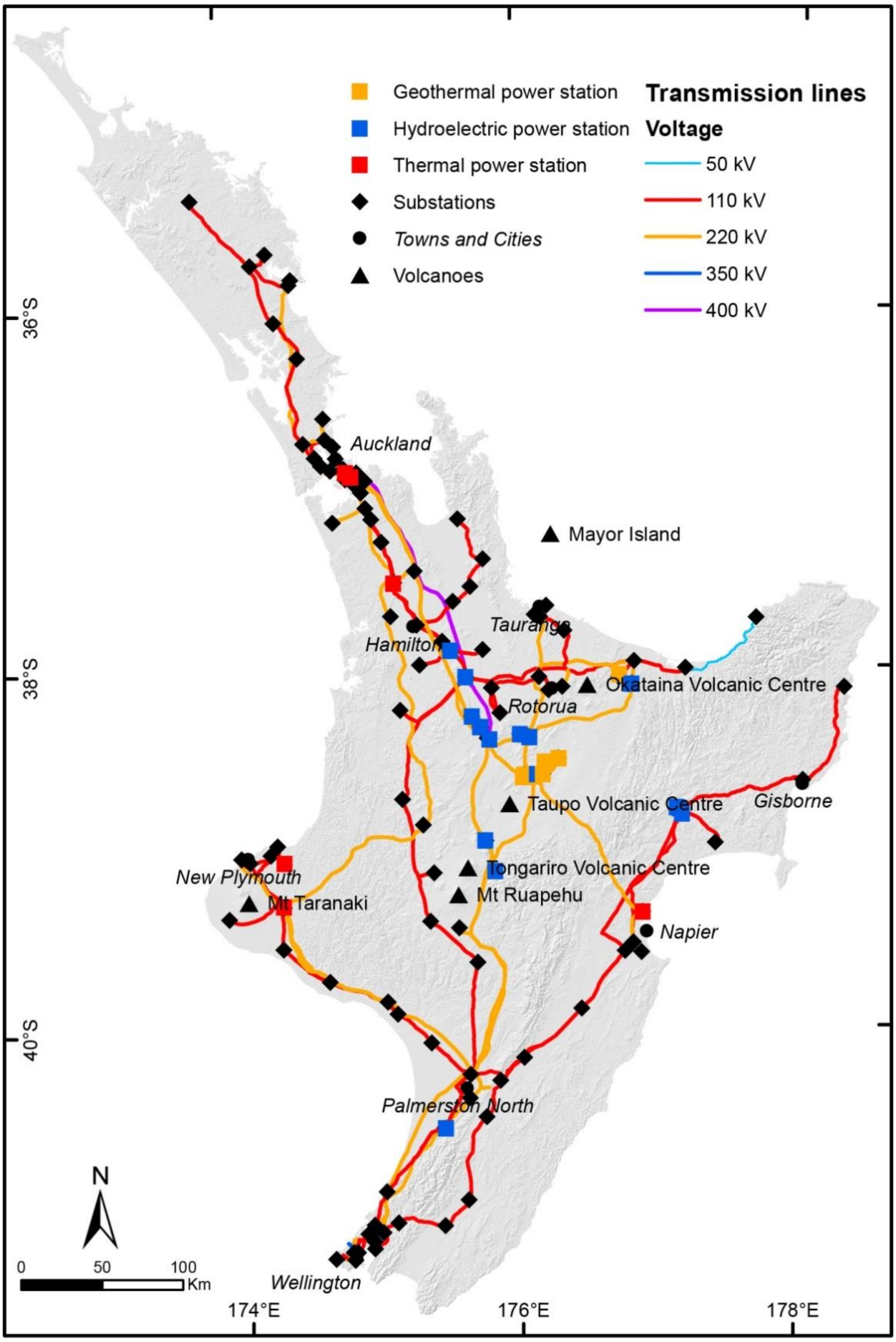


Figure 6.1: North Island electrical transmission network map showing generation sites (squares), substations (diamonds), the high voltage transmission lines (lines), main towns (circles) and volcanoes (triangles). Electricity network data from Electricity Authority (2014) and Transpower (2014).

6.3 Probabilistic tephra fall hazard assessment

The frequency and thickness of tephra falls at a location is dependent on eruption frequency and magnitude, physical characteristics of tephra particles and wind conditions. We use the probabilistic tephra fall hazard assessment developed in Chapter 5. This assessment uses TEPHRA2 (Bonadonna et al., 2005) to simulate 25,000 Volcanic Explosivity Index (VEI) 3–7 eruptions sourced from Mt. Taranaki, Mt. Ruapehu, Mayor Island, Okataina Volcanic Complex (OVC), Taupo Volcanic Complex (TVC) and Tongariro (Figure 6.1). Eruption parameters (e.g., erupted volume, column height, grainsize distribution) based on VEI classes and previous eruption deposits are stochastically sampled from statistical distributions for each simulation. For each simulation, wind profiles are randomly sampled from 15 years (1999–2013) of modelled wind data from National Centres for Environmental Protection (NCEP) and Atmospheric Research (NCAR) Reanalysis 1 database (Kalnay et al., 1996).

Annual eruption probabilities for Mt. Taranaki, OVC, Mt. Ruapehu and Tongariro are based upon specific eruption history studies (Turner et al., 2009; C. Wilson et al., 2009; Scott and Potter, 2014). Probabilities for the remaining volcanoes and conditional probabilities of different eruption sizes are from Jenkins et al. (2012), who derived these from global eruption databases and comparisons with similar volcano types. To estimate the tephra fall hazard at any location in the North Island, the annual occurrence probability of all simulations which reach each location and exceed a tephra thickness threshold are summed (i.e., a cumulative annual probability). Using this approach, the tephra thickness exceeded in a single eruption can be estimated for any North Island location on a 5 km × 5 km grid for any return period.

In Chapter 5 some limitations in the hazard assessment are acknowledged and should be considered when using the risk assessment presented here. The eruption probabilities derived from global comparisons to similar volcanoes are subject to uncertainty due to varying levels of data completeness. However, these eruption probabilities were used so that there was consistent coverage for all volcanoes. With continued research of eruption histories, uncertainties surrounding eruption probabilities can be reduced. In addition, the Auckland Volcanic Field was not included, as the hazard assessment only considered single vent volcanoes and calderas, therefore the risk in the Auckland region is likely to be underestimated.

6.4 Electricity transmission network

In New Zealand the electricity transmission network consists of generation sites, transmission and distribution lines and associated substations (Figure 6.1). In 2013, ~42,000 GWh of electricity was generated, split between energy types (percentage of total 2013 generation in parentheses): hydroelectric (54.5%); thermal (coal and natural gas) (24.7%); geothermal (14.5%); wind (4.8%); and bioenergy (1.4%) (MBIE, 2014). Generation sites are typically located some distance from demand centres (Transpower, 2014), therefore the transmission network connecting generation with demand centres is a critical part of the network. The New Zealand national transmission grid is a backbone of 110 and 220 kV alternating current circuits owned and operated by Transpower Ltd. (Transpower, 2014). The majority of the 11,764 km of transmission lines are located above ground, supported by ~41,000 support structures (concrete, wood and steel poles and steel lattice towers). Connecting the North and South Island networks is a 611 km long (40 km is a submarine cable under the Cook Strait) bi-directional high voltage direct current transmission line. Sub-transmission (33–110 kV) and distribution (<33 kV) lines which connect customers to the grid are owned and operated by various regional lines companies, but are not considered in this study due to a limited understanding of their performance during tephra falls. Substations of varying size are located at three points within the network: (1) at generation sites to input power into the transmission circuits, known as grid injection points (GIP); (2) between different transmission circuits to switch and control electricity flow and; (3) at the interface between transmission circuits and the lower voltage distribution network, known as grid exit points (GXP). Substations are owned and operated by Transpower Ltd. and regional lines companies based on their location within the network.

6.4.1 Vulnerability assessment

Nearly all components within the electricity transmission network are vulnerable to direct impacts from tephra fall. Because transmission networks extend above ground over large areas, they have high exposure, which increases their vulnerability to tephra falls. Table 6.1 summarises common impacts (disruption and damage) to different parts of the transmission network, derived from post-eruption impact assessments and experimental data.

6.4.1.1 Volcanic fragility function derivation methodology

To estimate the risk to the electrical network, a relationship between tephra fall intensity (i.e., tephra thickness) and impact (disruption or damage) is required. This relationship is typically represented as a fragility function which gives the probability of a particular asset reaching a certain impact level/intensity (Rossetto et al., 2013; Tarbotton et al., 2015). The method to derive volcanic fragility functions and the electricity transmission functions themselves are presented in Chapter 4 (Sections 4.4.4 and 4.5.3, respectively) and are repeated and summarised here for this specific assessment.

To derive fragility functions for electricity assets, we use data from global post-eruption impact assessments, laboratory experiments and expert judgment. Volcanic impact data for each asset type are prepared such that each data point is assigned two attributes: (1) a tephra thickness at which impact occurred; and (2) an impact state (IS) value which describes the observed impact intensity. Here we use the ISs described in Chapter 2 (Table 2.12): IS_0 – no damage (lowest state); IS_1 – cleaning required (minor damage); IS_2 – repair required (moderate damage); and IS_3 – replacement or financially expensive repair (highest state). Each data point is assigned an IS based on the comparison of documented impact descriptions to those in Table 2.12. Data are ordered by increasing tephra thickness and are grouped into thickness bins, such that each bin has approximately the same number of data points (Figure 6.2). The limited number of data prevented splitting the dataset into more than three thickness bins.

The probability of an asset being equal to or exceeding each IS is calculated for each thickness bin using the relative proportions of each IS in that bin. Because ISs are sequential, in that reaching IS_i implies IS_{i-1} has been reached, the probability of an asset being equal to an IS can be calculated. Discrete tephra thickness values are obtained by taking the median of each thickness bin. For each IS, a segmented linear equation is used to fit data and produce individual fragility functions. This simplified approach is taken because the limited number of data does not justify fitting more complex mathematical functions, such as a lognormal cumulative distribution function, which are commonly used in other natural hazards fields (e.g., Porter et al., 2007; Mas et al., 2012; Rossetto et al., 2013).

Due to the limited post-eruption impact data (in respect of the number of data and their representativeness of all impacts), expert judgment is used to modify the probability values of resulting functions so that mathematical fitting rules are not violated. Fitting rules (explained in more detail in Section 4.4.4.2) are: (1) no impacts occur at 0 mm tephra thickness; (2) individual functions are sequential; (3) individual functions can converge but not intercept; and (4) functions are non-decreasing, i.e., the probability of each function does not decrease as tephra thickness increases.

6.4.1.2 Generation fragility functions

Operating conditions and impact mechanisms between the three generation types (HEP, geothermal and thermal) are different and should be considered in volcanic risk assessments. Sufficient impact data were not available to robustly derive fragility functions for each generation type. Instead a generic (average) fragility function is derived for all generation types and subsequently modified by expert judgment to produce fragility function sets for each generation type (Figure 6.3). Based on available post-eruption impact data, HEP stations are likely to have the highest vulnerability of the three generation types (Figure 6.3). This is because reservoir water could become contaminated with tephra and pass through the turbines, causing significant abrasion damage, thereby reducing turbine efficiency (e.g., Meredith, 2007). Tephra could also block and/or limit the flow of water through pipes connecting the storage reservoir to the turbines. Turbines at geothermal and thermal power stations are closed systems and will therefore not suffer tephra-induced abrasion (i.e., lower vulnerability). Nevertheless, water is required at these stations for cooling purposes and tephra-contaminated water might cause abrasion damage to water pumps and heat exchangers, increasing their vulnerability. At thermal power stations, air is required for combustion and cooling purposes and tephra fall could cause blockage of air intake filters and abrasion of cooling fans. Because air is not required for combustion at geothermal power stations, we estimate the vulnerability of thermal power stations to be higher than that of geothermal stations (Figure 6.3).

While there are no case studies which document impacts at IS_3, we believe this is due to under reporting and that these impacts are likely to occur in the future. Therefore, for the fragility functions we estimate the probability of generation sites being at IS_3 to be <0.4 up to 100 mm tephra thickness (Figure 6.3).

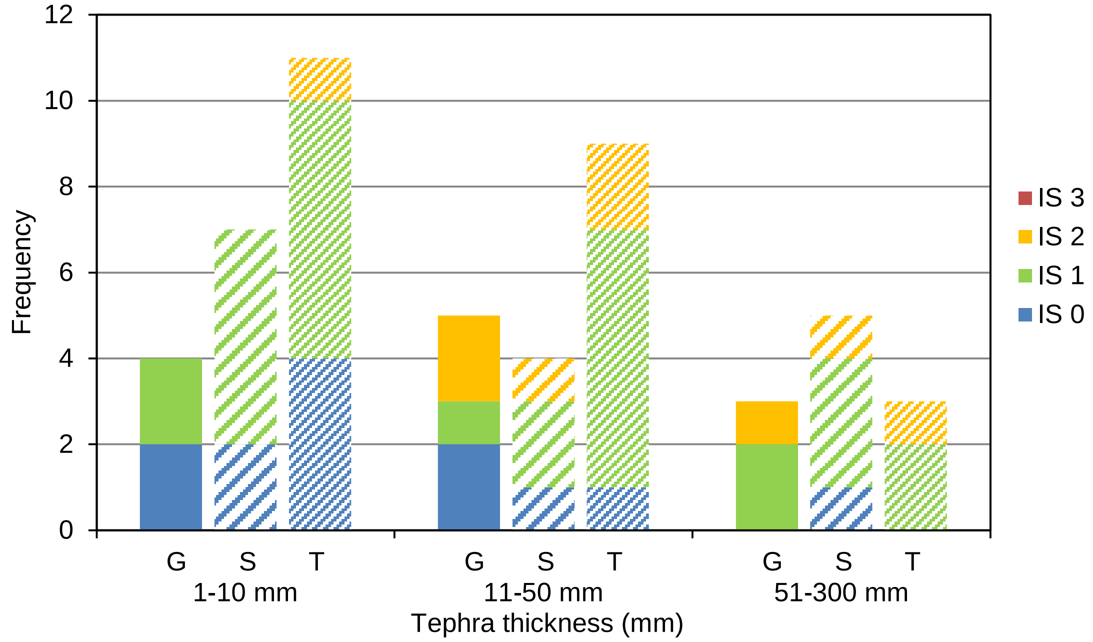


Figure 6.2: Available post-eruption impact data for generation sites (G), substations (S) and transmission lines (T) classified into impact states (IS) and binned by tephra thickness.

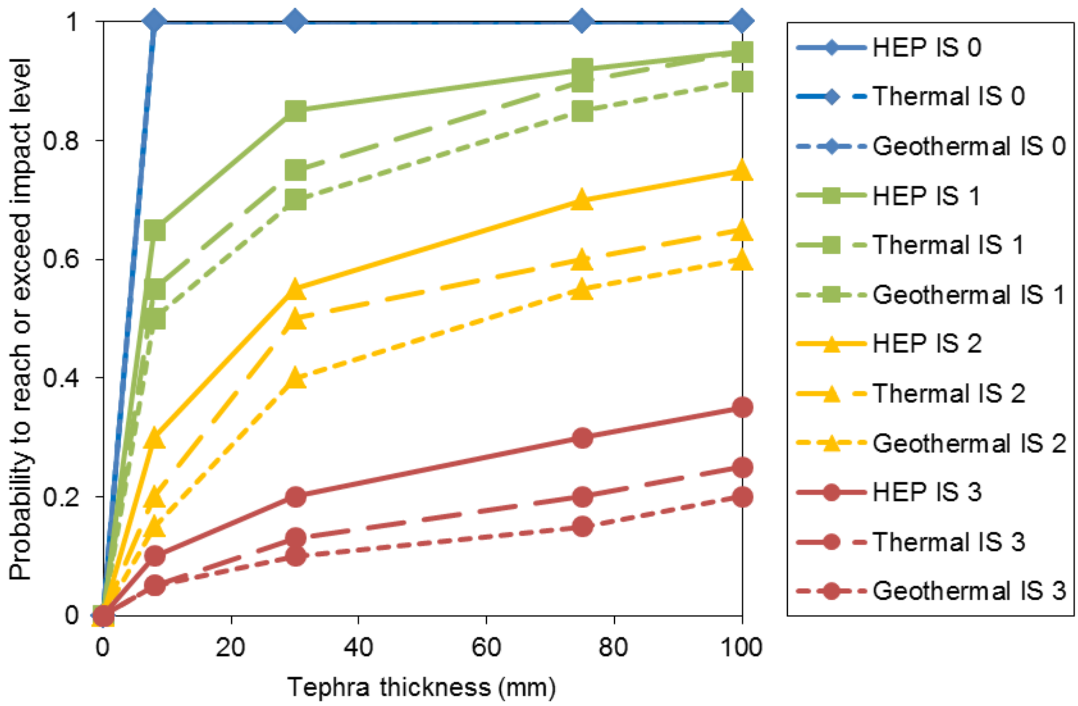


Figure 6.3 Fragility functions giving the probability of electrical generation sites equalling or exceeding each impact state (IS) as a function of tephra thickness for hydroelectric power (solid line), thermal (long dash) and geothermal (short dash) generation.

6.4.1.3 Substation fragility functions

Substations are vulnerable to tephra fall due to the range of sensitive equipment they contain and because they are key nodes for the transmission system. There are 16 post-eruption impact assessments available and the majority of the empirical data can be classified as IS_1 (Figure 6.2). Few instances of substation impact $\geq IS_2$ such as transformer failure after the 1991 Mt. Hudson, Chile eruption (T.M. Wilson et al., 2009) have been documented (Figure 6.2), indicating that equipment damage is less common than cleaning related disruption. However, like generation sites, IS_3 is likely to occur in future eruptions and is therefore estimated with a probability of ≤ 0.15 in the fragility function (Figure 6.4). The higher likelihood of a substation being at IS_1 is represented in Figure 6.4, with the IS_1 fragility function retaining a probability of between 0.3–0.6 for any given tephra thickness. This fragility function set assumes that substations are located outside and exposed to direct tephra fall. If a substation is covered, the overall fragility will be governed by the fragility of the roof and building structure.

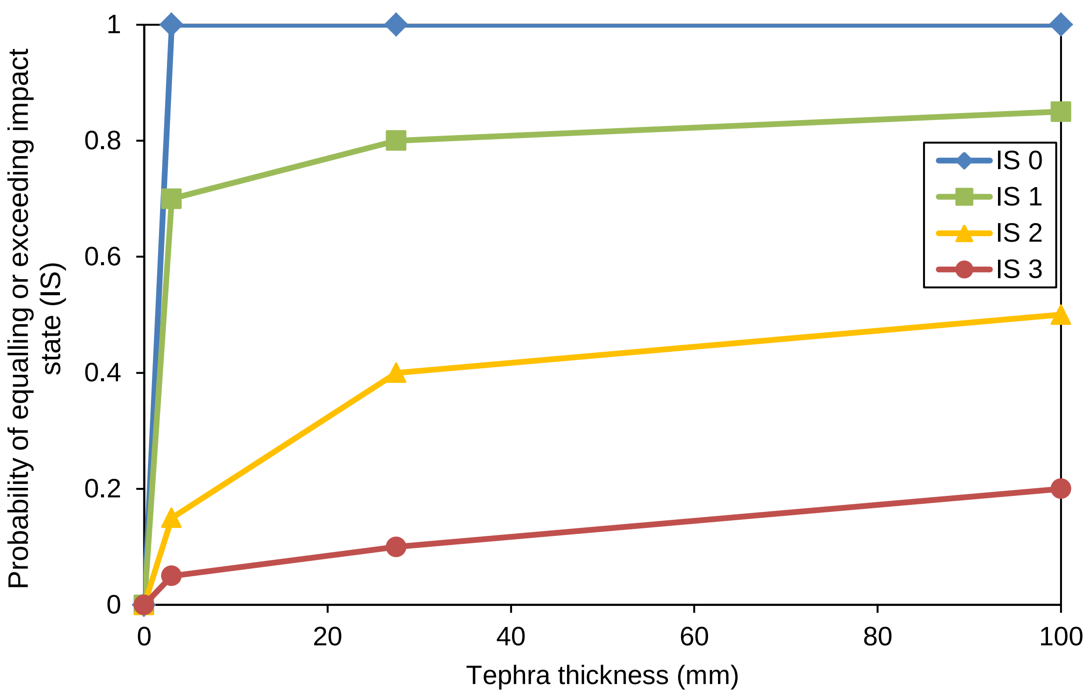


Figure 6.4: Fragility functions giving the probability of substations equalling or exceeding each impact state (IS) as a function of tephra thickness.

6.4.1.4 Transmission fragility functions

Transmission lines are vulnerable to tephra fall impacts resulting in permanent or temporary disruption of electricity transmission. The majority of the post-eruption impact data are classified as IS_1 (Figure 6.2). Documented disruption is typically caused by flashover, controlled shutdowns to prevent damage and cleaning of equipment. Wardman et al. (2012) conducted laboratory experiments to systematically investigate flashover occurrence; we use their data to supplement the post-eruption impact data to derive the IS_1 function (Figure 6.5). Given that flashover is far less likely with dry tephra (Wardman et al., 2012), the fragility functions should only be used to estimate insulator flashover in the presence of wet or moist tephra deposits. Physical damage such as line breakage (IS_2) has occurred; however, it is less common. More severe damage (IS_3) has not been documented, although this could potentially occur in future eruptions and therefore an estimated value is included in the fragility functions.

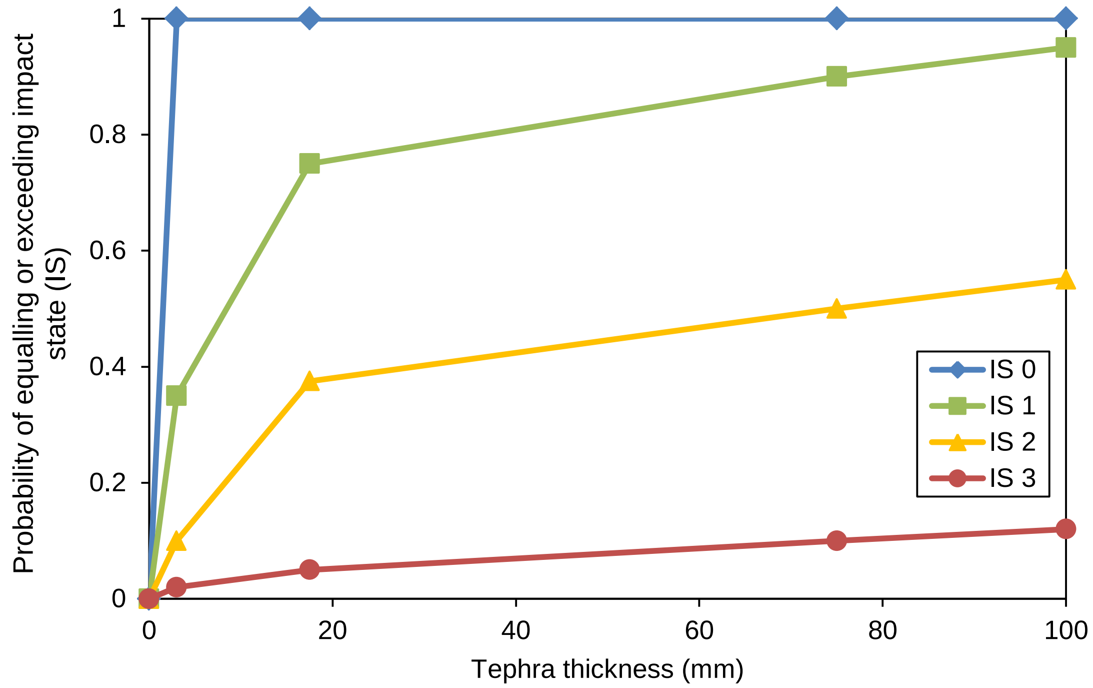


Figure 6.5: Fragility functions giving the probability of transmission lines equalling or exceeding each impact state (IS) as a function of tephra thickness.

6.4.1.5 Uncertainty and limitations

There are uncertainties and limitations with our volcanic fragility functions which should be considered when using the results of this risk assessment. The data used to derive the electricity fragility functions come from a limited number of observations. Using the exceedance probability of each IS for a particular tephra thickness, we account for some of the data uncertainty. For each thickness there is a certain probability that the electricity site will be in any one of the four ISs (see Section 6.4.2).

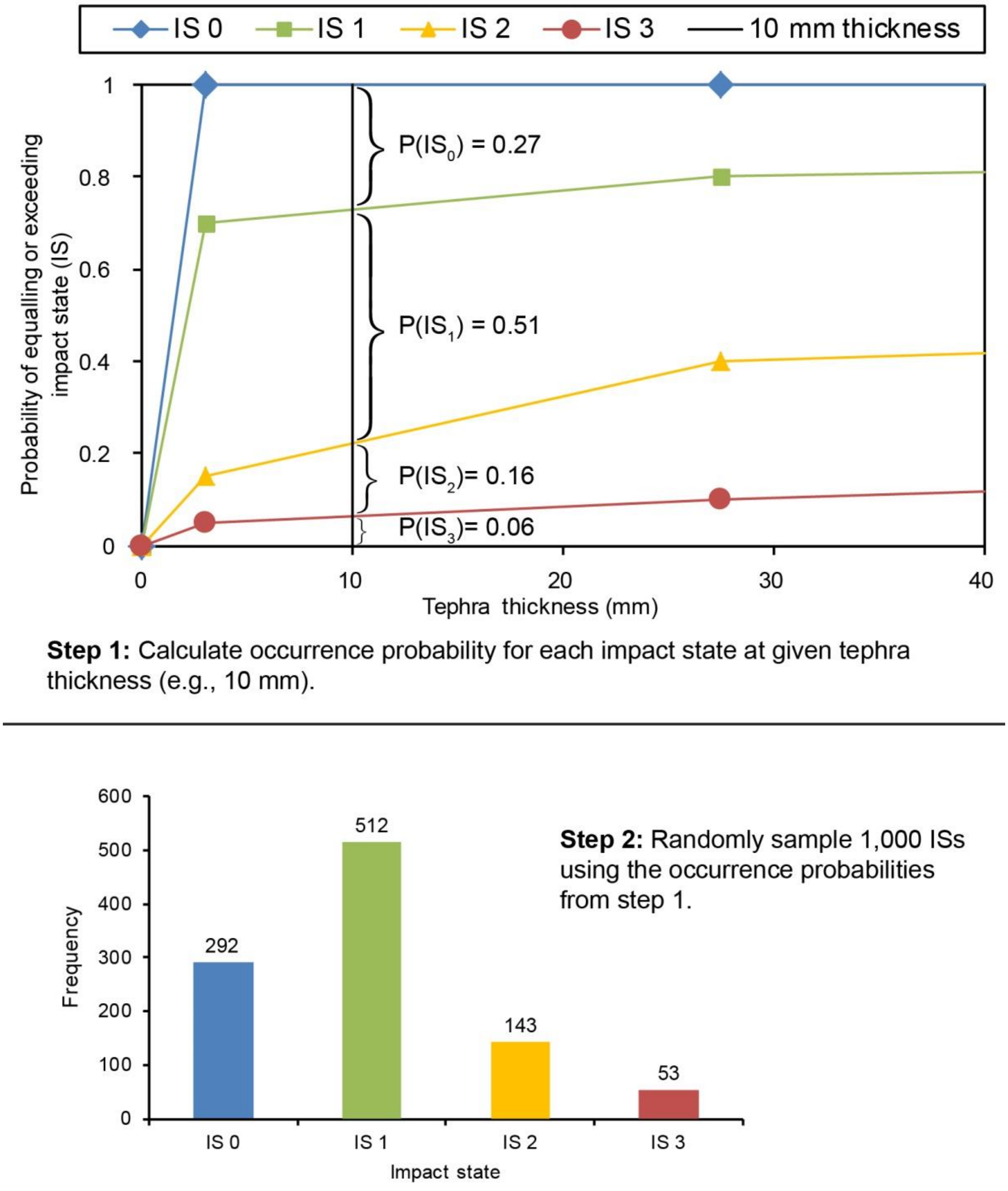
The post-eruption impact data used typically reflect the wide range of different infrastructure types and configurations used worldwide (Jenkins et al., 2014), thus there is rarely a standard electrical infrastructure typology with which to assess vulnerability to tephra fall. Our functions only consider aggregated electricity typologies ('generic' typologies) and we anticipate some typologies and/or configurations might have increased or decreased vulnerability. In addition, the derived fragility functions apply to individual sites in isolation from the rest of the network as we have not considered the interdependency of the different assets in this assessment. We have not conducted specific site assessments of New Zealand electricity transmission sites and if a more detailed volcanic risk assessment is required, we recommend that vulnerability be assessed on a site-by-site basis.

A factor that is not accounted for in either the hazard or vulnerability assessments is the duration of tephra fall. While TEPHRA2 accounts for the eruption and tephra particle sedimentation duration, the output does not include the duration of tephra accumulation on the ground. Tephra fall duration may influence impact occurrence (e.g., abrasion can occur over long time periods) and the response of electricity site operators (e.g., tephra clean-up might be undertaken multiple times during prolonged tephra falls, altering the assets' tephra exposure).

6.4.2 Risk assessment methodology

Electricity transmission network data were obtained in geographic information system format from publicly available sources (Electricity Authority, 2014; Transpower, 2014). Centroid points were obtained from polygons for generation and substation sites and lines were obtained for transmission lines. Transmission lines were divided into 1 km segments as this was determined to be an appropriate scale to assess risk, due to the spatial resolution of the tephra fall hazard model (interpolated to a 1 × 1 km grid) and given the limitations of the transmission fragility functions. The midpoint of each line segment was used to obtain a tephra thickness to assess risk. The total number of insulators per 1 km segment of transmission line was not obtained as it typically only takes one insulator to flashover for a whole line to be disrupted. Additional attribute data (e.g., transformer type, turbine type, cooling system, insulator type, line support) were not obtained as there are limited data regarding how tephra will impact these specific components.

The tephra thickness at each electricity site and transmission line segment midpoint was obtained from the North Island probabilistic tephra fall model developed in Chapter 5. This hazard model gives the tephra thickness to be exceeded in a single eruption from any of the six volcanoes for any return period. For this risk assessment, 500 and 2,500 year return periods were selected. These two return periods are used as they are the two most common return periods used in natural hazard analysis and for building codes in New Zealand (Standards New Zealand, 2004).



$$\| IS \| = \frac{(292 \times 0) + (512 \times 1) + (143 \times 2) + (53 \times 3)}{1000}$$

IS = 1

Step 3: Obtain a single IS by taking a weighted average of all generated ISs and rounding to nearest integer.

Figure 6.6: Methodology used to estimate a discrete IS for each electricity transmission site using fragility functions and tephra exceedance thicknesses.

For a given tephra thickness, an electricity site has a probability of being in one of four impact states given by the fragility functions (Figures6.3–6.5). While it is useful to know these probabilities, it is difficult to map and present these four values for all electricity sites to electricity transmission operators. Therefore, a single IS is estimated for each electricity site, an approach used by New Zealand's RiskScape software (RiskScape, 2014). To predict the IS of a site, 1,000 ISs are randomly generated based on the relative occurrence probabilities of each IS for a given tephra thickness. A weighted average of these ISs is taken and rounded to the nearest integer to give a single IS for that particular electricity site. This process is shown in Figure 6.6. By randomly determining ISs, this approach further accounts for uncertainty within the fragility functions. The ISs are displayed on maps using colour keys to represent different levels of risk for the 500 and 2,500 year return periods (see Section 6.5). The probability of insulator flashover (IS_1) can be obtained from Figure 6.5 using tephra exceedance thicknesses from Figure 6.7.

Table 6.2: Length of transmission lines, number of substations and generation sites in each impact state for return periods of 500, 2,500 and 10,000 years.

Return period	Asset type	Impact states (IS)			
		IS_0	IS_1	IS_2	IS_3
500 years	Transmission lines	2,380 km (37%)	3,309 km (51%)	561 km (9%)	147 km (2%)
	Substations	52 (46%)	55 (49%)	5 (4%)	0 (0%)
	Generation sites	8 (27%)	11 (37%)	9 (30%)	2 (7%)
2,500 years	Transmission lines	650 km (10%)	3,706 km (58%)	1,675 km (26%)	367 km (6%)
	Substations	22 (20%)	65 (58%)	20 (18%)	5 (4%)
	Generation sites	3 (10%)	3 (10%)	14 (47%)	10 (33%)
10,000 years	Transmission lines	148 km (2%)	2,255 km (35%)	2,786 km (43%)	1,207 km (19%)
	Substations	3 (3%)	52 (46%)	37 (33%)	20 (18%)
	Generation sites	0 (0%)	4 (13%)	6 (20%)	20 (67%)

Impact states are: IS0 – no damage (lowest state); IS1 – cleaning required (minor damage); IS2 – repair required (moderate damage); and IS3 – replacement or financially expensive repair (highest state) (see Table 2.12 for detailed descriptions of each state). Percentages are the percentage of total North Island network and do not always sum to 100% due to rounding.

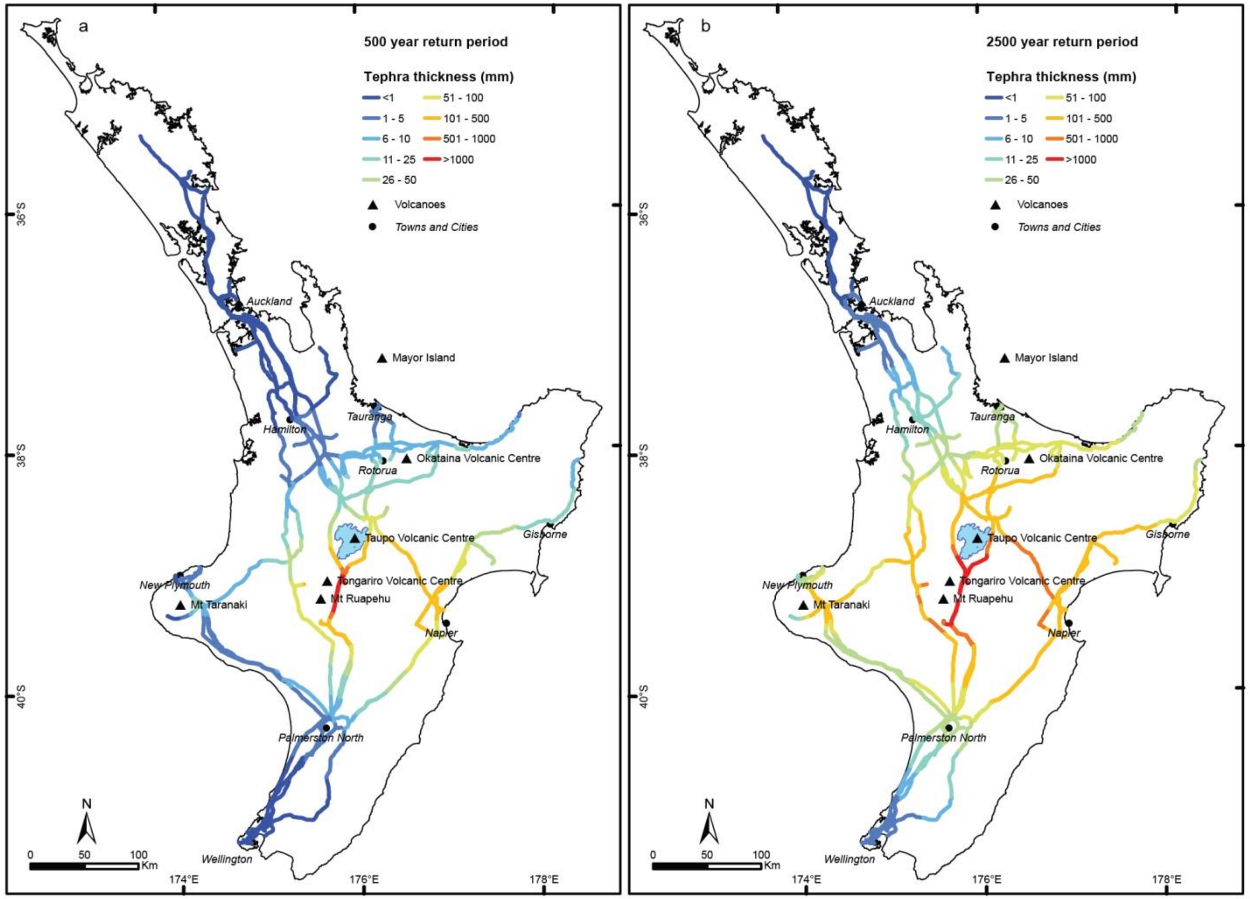


Figure 6.7: Probabilistic tephra fall hazard showing exceedance thicknesses on the high voltage transmission lines in the North Island, New Zealand for return periods of **A** 500 years and **B** 2,500 years. Main towns and cities indicated with circles and source volcanoes with triangles.

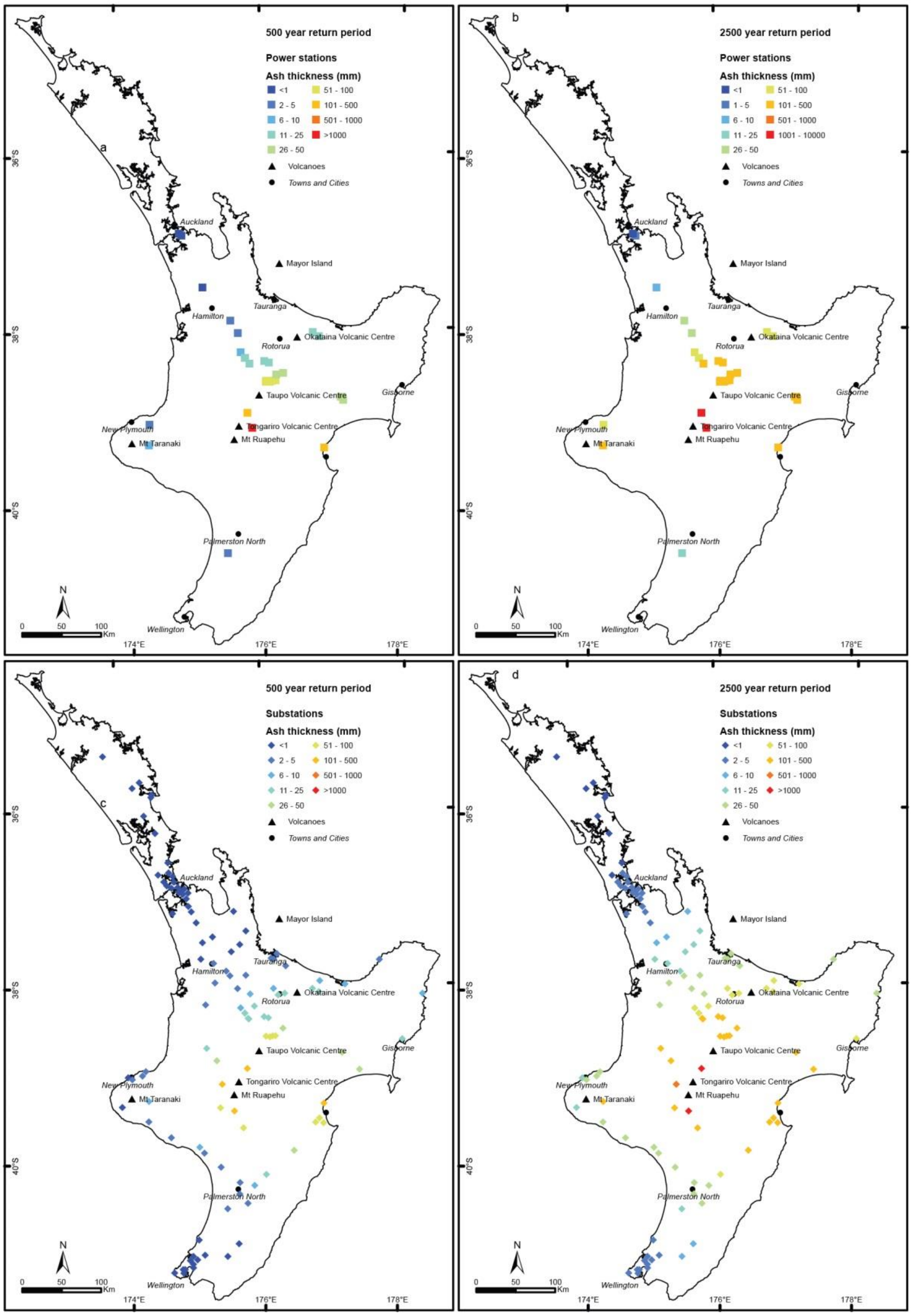


Figure 6.8: Probabilistic tephra fall hazard showing exceedance thicknesses on electricity substations and generation sites in the North Island, New Zealand for return periods of **A** 500 years and **B** 2,500 years. Main towns and cities indicated with circles and source volcanoes with triangles.

6.5 Results

For each electricity generation, substation and transmission line site, volcanic risk is estimated and mapped as IS exceedance for a single eruption from any of the six North Island volcanoes for a 500 and 2,500 year return period. For example, if an electricity site is displayed as IS_2 for the 500 year return period, then on average, we would expect that every 500 years that site will be equal to or exceed IS_2 from a single eruption from one of the six volcanoes. Figures 6.7–6.8 show tephra exceedance thicknesses for the North Island electricity transmission infrastructure are greatest immediately to the east of Mt. Ruapehu and Tongariro for both return periods considered. Refer to Chapter 5 for tephra fall hazard maps for the whole North Island (Figures 5.6–5.11). Figure 6.9 presents hazard curves for key generation and substation sites, showing tephra thickness exceedance as a function of the return period. Figures 6.10–6.11 show the risk assessments for generation sites, substations and transmission lines. The highest risk is in the central North Island, corresponding to the high tephra exceedance thicknesses. Table 6.2 shows the number of generation and substation sites and length of transmission lines in each of the ISs for three return periods (500, 2,500 and 10,000 years). It can be seen that as the return period increases the number of sites at IS_3 also increases as larger eruptions become more frequent over longer return periods.

6.6 Discussion

Tephra thickness is greatest immediately east of Mt. Ruapehu and Tongariro (Figures 6.7–6.8) and electrical infrastructure in this proximal area (within 15–20 km of the volcanoes) can be expected to experience ≥1 m of tephra for return periods of ≥500 years. The primary reasons tephra thickness is greatest here are that these are the two most active volcanoes in the North Island and that the wind predominantly blows towards the east dispersing tephra in this direction. We would expect infrastructure located further towards the east, in areas around Napier and Gisborne, to experience thicknesses exceeding 50 mm for return periods of ≥500 years. Mt. Taranaki has a lower annual eruption probability than Mt. Ruapehu and Tongariro (Table 5.3) and therefore contributes less to the overall tephra fall hazard. However, as the return period increases, transmission lines immediately east of Mt. Taranaki will experience greater tephra thickness, exceeding 100 mm over a 2,500 year return period. Due to the predominant wind direction towards the east and the concentration of volcanoes within the central North Island, electricity sites towards the north (Auckland) and south (Wellington) of the island have lower tephra exceedance thicknesses (Figures 6.7–6.8).

Figure 6.9 presents hazard curves for key generation and substation sites, showing tephra thickness exceedance as a function of the return period. By deriving continuous hazard curves for a range of tephra thicknesses, volcanic risk analysis is not fixed to pre-defined thickness thresholds or return periods. For a given tephra thickness, e.g., 1 mm, the hazard curves show a wide range of return periods; 40–1,000 years for generation sites (Figure 6.9A) and 50–1,800 years for substations (Figure 6.9B), depending on site location. For a given tephra thickness, electricity generation at Karapiro (HEP) and Huntly (thermal) and substations at Otahuhu and Haywards have the highest return periods. These sites are located further from the central North Island volcanoes and are therefore less affected by tephra falls (Figure 6.9C). Conversely, sites such as Tokaanu (HEP generation) and Tangiwai (substation), which are located close to Mt. Ruapehu, have the lowest return periods and can be expected to exceed 1 mm of tephra, on average, every 40–50 years. The hazard curves for generation and substation sites in Stratford show a different trend to other sites. The primary reason for this is that Stratford is mostly influenced by eruptions from Mt. Taranaki, whereas other sites are influenced by eruptions from multiple volcanoes. Effectively, the tephra fall hazard at Stratford is controlled by the eruption probability of Mt. Taranaki, whereas other sites are influenced by an aggregation of six volcanoes; therefore, hazard curves follow a similar trend.

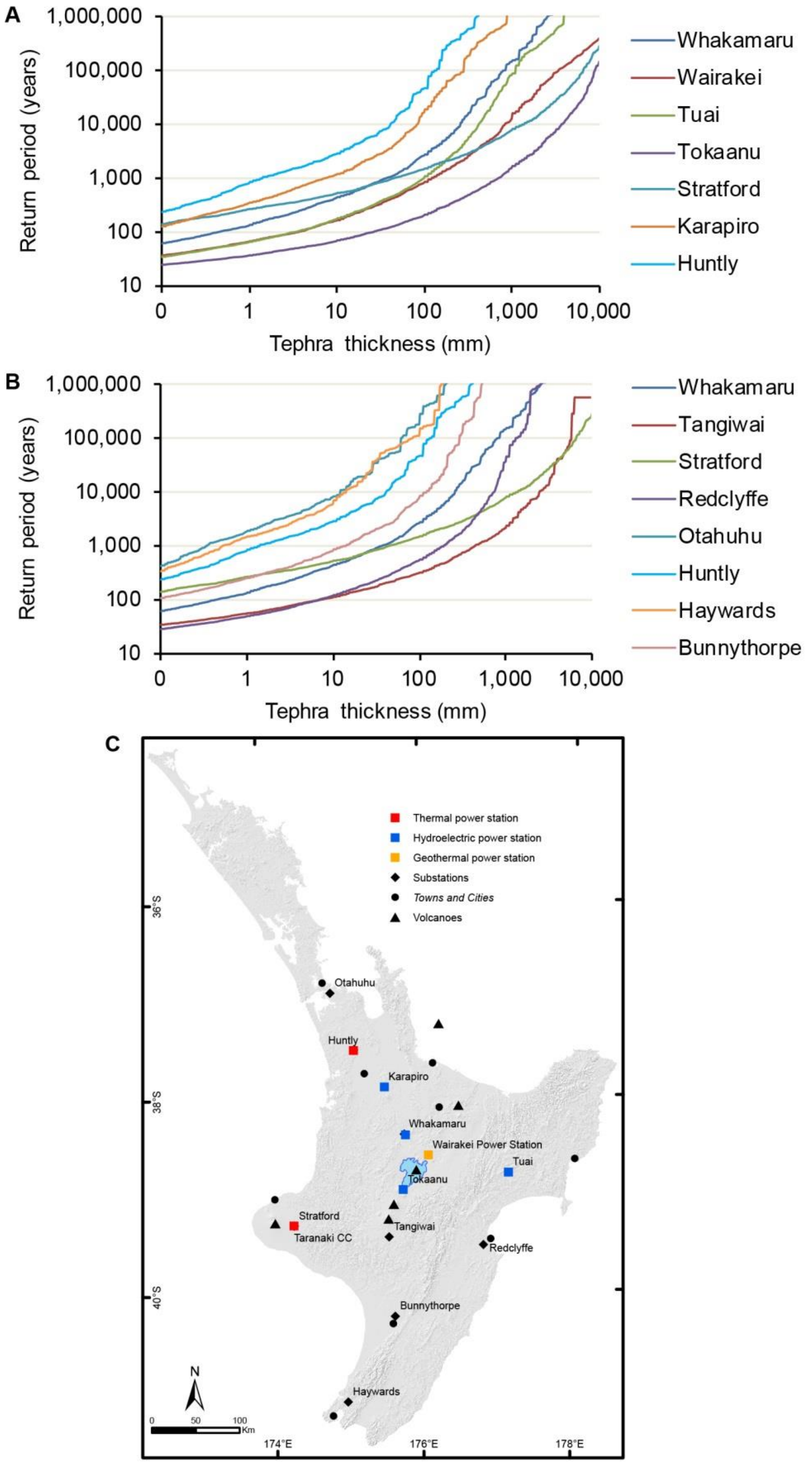


Figure 6.9: Hazard curves showing return period as a function of tephra thickness for **A** critical generation sites and **B** critical substations. **C** shows substation and generation site locations. Return period is approximately the inverse of annual exceedance probability.

The risk analysis of electricity generation sites shows that for the 500 year return period there are two HEP stations (Tokaanu and Rangipo) which will be at IS_3 (Figure 6.10A). At IS_3, abrasion damage is likely to occur to the turbines at these stations which may require at least a temporary shutdown to repair or replace turbines and associated components. The risk for these two stations is likely to be underestimated. Our risk assessment does not take into account the influence of tephra entering the wider HEP catchment area and being transported through the network to the turbines, nor does it account for the long term exposure of turbines to tephra particles. Both of these stations are part of the 360 MW Tongariro Power Scheme in the central North Island, which has a catchment of >2,600 km^2 (Genesis Energy, 2015). If tephra entering this catchment is considered then impacts could be more severe, requiring more expensive repair. A more detailed assessment of tephra entering and moving through a HEP station catchment is required to fully assess the risk; this is beyond the scope of this chapter. The lowest risk (IS_0) generation sites over a 500 year return period are those in the Hamilton region and one thermal station near New Plymouth (Figure 6.10A) which are likely to continue electricity generation. For the 2,500 year return period, the number of generation sites at IS_3 increases to 10 (Table 6.2), including a number of geothermal power stations to the north of the TVC (Figure 6.10B). In addition, all of the HEP stations between the TVC and Rotorua will experience IS_2 or greater. If multiple generation sites are impacted during a single eruption then electricity supply within the North Island could be severely disrupted and there may be an increased reliance on generation from the South Island, provided substations and transmission lines remain operational.

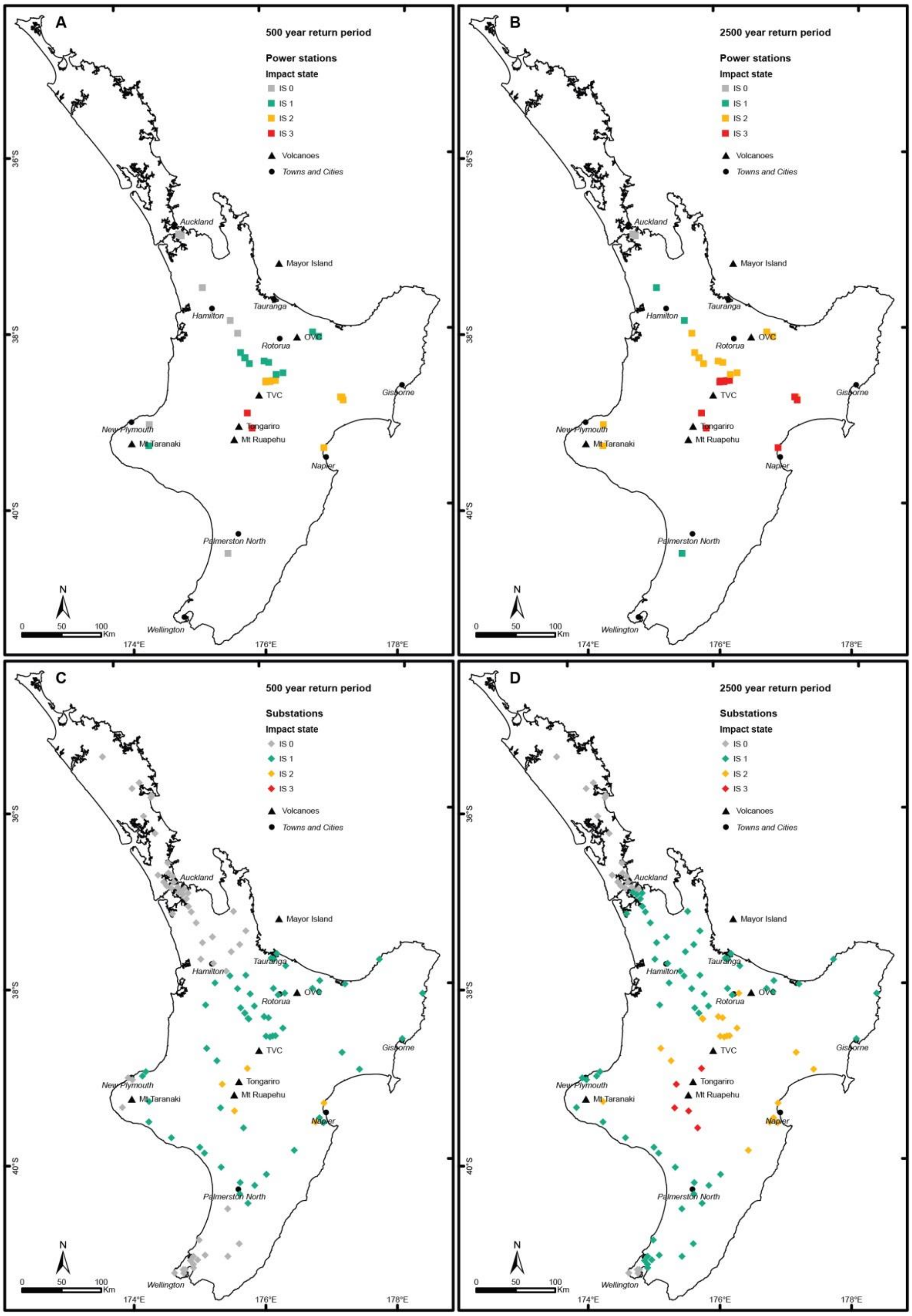


Figure 6.10: Impact states for electricity generation sites and substations. **A** and **B** show the impact state to be equalled or exceeded for the 500 and 2,500 year return periods respectively for generation sites. **C** and **D** show the impact state to be equalled or exceeded for the 500 and 2,500 year return periods respectively for substations. Main towns and cities indicated with circles and source volcanoes with triangles.

The risk assessment of substations is crucial as they are critical nodes between electricity generation and transmission. A generation site may be unaffected by tephra fall and may continue to generate electricity, yet if its associated substation has been impacted then electricity cannot be transmitted to the transmission grid. The highest risk of substation impact is in the central North Island, extending towards the east, for both return periods (Figure 6.10C–D). For the 500 year return period, the majority of North Island substations are equal to or exceed IS_1, a level associated with cleaning of equipment. Disruption may result from substation gravel ground cover becoming filled with tephra, causing changes in resistivity. These changes in resistivity can make the substation unsafe for personnel as the gravel cover is designed to be at a known resistivity to accommodate any transmission faults (e.g., short circuits) (IEEE, 2000; Wardman et al., 2012). For the 2,500 year return period, ~80% of the North Island substations equal or exceed IS_1 (Table 6.2 and Figure 6.10D); this includes a number of substations in the Auckland and Wellington regions. Three critical substations, Haywards, Bunnythorpe and Otahuhu (see Figure 6.9C for locations) are at IS_1 and Whakamaru is at IS_2. These substations are critical to the transmission of electricity within the North Island and between the North and South Islands. If any of these substations are impacted during an eruption there is likely to be widespread disruption of electricity transmission throughout the North Island and possibly the South Island. As such, it is critical that these substations have tephra preparedness and clean-up plans developed prior to any future eruption in order to limit disruption caused by any tephra fall (e.g., Wardman et al., 2012; T.M. Wilson et al., 2014). A more robust solution would be to move critical parts of substations inside buildings to limit the direct accumulation of tephra on sensitive components and equipment. However, the expense of this action will need to be justified through cost-benefit analysis.

The functionality of electricity transmission lines is critical, as these connect areas of generation with areas of demand. Figure 6.11A–B shows the ISs which will be equalled or exceeded for the transmission lines in the North Island for the 500 and 2,500 year return periods. The highest IS (IS_3) occurs to the east of Mt. Ruapehu and Tongariro, suggesting that in this region transmission lines could sustain damage, such as pole and line breakage, from thick tephra deposits. This type of impact would cause significant and possibly widespread disruption to electricity transmission until repairs are undertaken. A more accurate assessment of this damage mechanism would need to include the characteristics (design load) of the transmission support structures and the tephra density and moisture content (wet dense tephra increases static loads; Johnston et al. 2000). For the 500 year return period the majority of the transmission network would equal or exceed IS_1, indicating flashover, minor disruption and cleaning of lines is highly likely. Further from the central North Island volcanoes, the transmission network is likely to remain unaffected (IS_0). For the 2,500 year return period, the transmission line between Napier to north of TVC is generally IS_2, with small sections of IS_3 (Figure 5.11B). These small changes are the result of slight changes in tephra thickness and the random sampling of IS for each transmission line segment.

The main cause of tephra-induced disruption to transmission lines is insulator flashover (Wardman et al., 2012), and for this risk assessment flashover is considered to occur at IS_1. Because flashover is much more likely to occur in the presence of moist/wet tephra deposits than dry (Wardman et al., 2012), the assessments relating to flashover are only applicable in wet conditions. The insulators most at risk from flashover are those on transmission lines crossing the central North Island to the west and east of Mt. Ruapehu. For a 500 year return period, the highest risk area is a segment of 220 kV transmission line adjacent to Mt. Ruapehu and in the Napier region, where insulators have a high probability of flashover for this return period. Extending the return period out to 2,500 years, the highest risk areas will cover a larger area in the central North Island. Over a 2,500 year return period, ~3,700 km of transmission lines are likely to be at IS_1 and suffer from insulator flashover (Table 6.2). In addition, there is an increased risk of flashover in the immediate vicinity of Mt. Taranaki as the eruption frequency here increases. In the Taranaki region there is a critical point at Stratford, where a number of thermal power stations connect to the national transmission grid, which could be impacted.

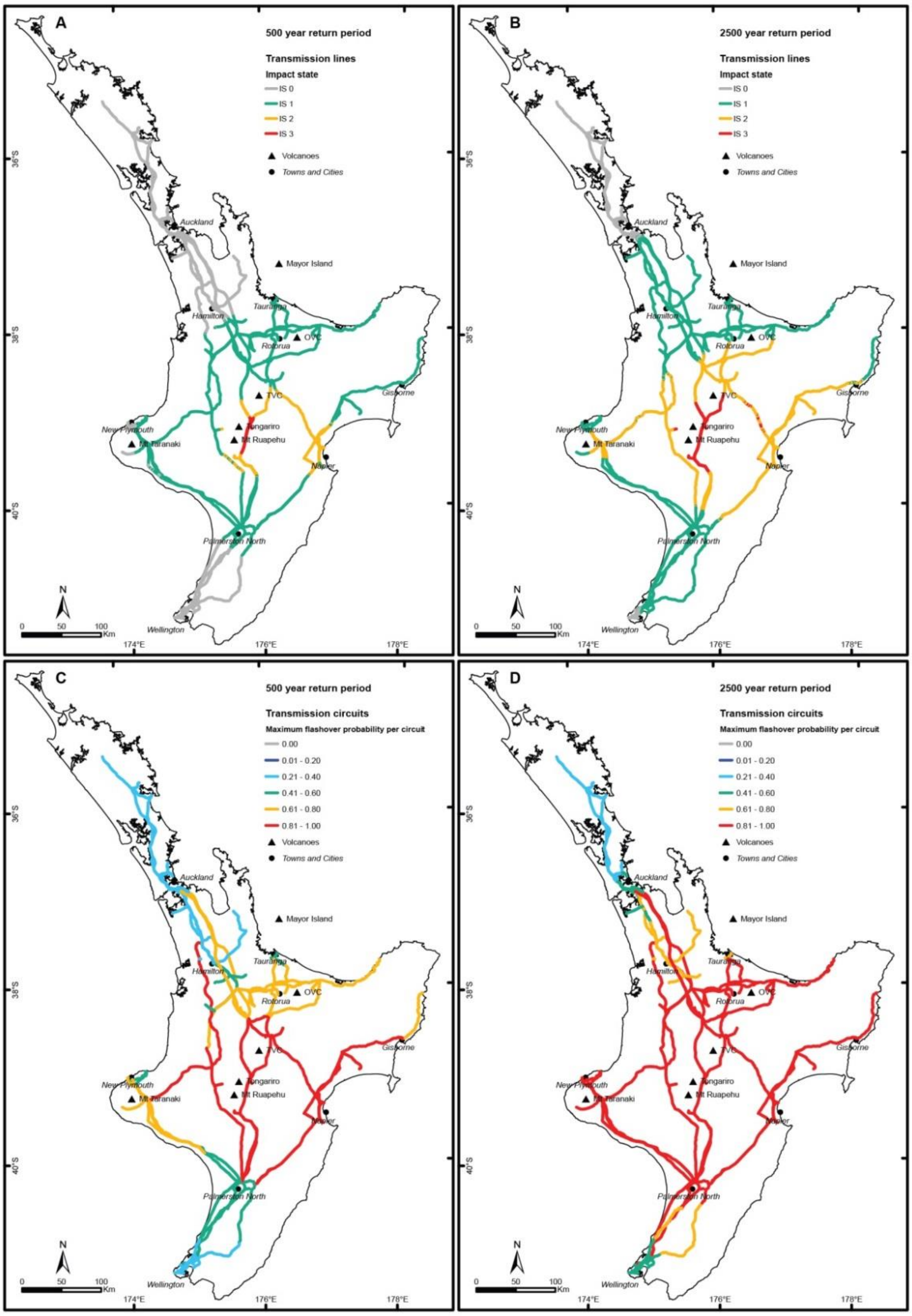


Figure 6.11: Risk assessment and disruption of electricity transmission lines to due tephra fall impacts. **A** and **B** show the impact state to be equalled or exceeded for the 500 and 2,500 year return periods respectively. **C** and **D** show flashover probability for individual circuits to indicate likely disruption from a single flashover occurrence for the 500 and 2,500 year return periods respectively. Main towns and cities indicated with circles and source volcanoes with triangles.

When a single flashover occurs, the circuit breaker on the circuit can be tripped, causing disruption to electricity transmission on that particular circuit (Wardman et al., 2012). Some circuit breakers have an auto-reclose system which automatically recloses the circuit breaker after a flashover. However, if tephra is still present on an insulator it may cause another flashover after the circuit is reconnected. This cycle can continue until the circuit is manually disconnected or tephra is removed from insulators. In essence, a single occurrence of insulator flashover can cause disruption to an entire circuit which could be hundreds of kilometres long (G. Wilson et al., 2014). Therefore, to assess the potential disruption from insulator flashover on individual circuits, we take the highest flashover probability on each circuit, as that will be the weakest link, and apply that value to the entirety of individual circuits (Figure 6.11C–D). Using this approach, for a 500 year return period the highest risk to circuit disruption is on nine 110 and 220 kV circuits in the central North Island both west and east of Mt. Ruapehu and Tongariro (Figure 6.11C). Other circuits near Mt. Taranaki and around Rotorua have slightly lower flashover probabilities. Over a 2,500 year return period (Figure 6.11D), the majority of the north-south circuits have high flashover probabilities. Again, the circuits least at risk of flashover are those in the north and south of the island, further away from the volcanoes. If any of the north-south transmission circuits become disrupted during a future eruption, then transmission to Auckland, the North Island’s largest consumer (Transpower, 2014), could be limited. This could have potential flow on impacts to other sectors which rely on constant electricity supply. In the case of circuits becoming disrupted, electricity transmission could be re-routed to unaffected parts of the network for continued supply. The feasibility of re-routing needs to be considered from a network analysis point of view, as there may be capacity constraints on certain parts of the network which need to be considered; this is beyond the scope of this chapter.

Our risk assessment identifies areas of high risk to the North Island electricity transmission network, highlighting in broad terms areas where mitigation techniques could be applied to reduce volcanic risk. Because our fragility functions consider generic electricity infrastructure, we cannot advise on the application of appropriate mitigation treatments. In order to apply appropriate mitigation treatments, individual site vulnerability assessments, which account for local variations in vulnerability, are required. Cost-benefit analyses can then be undertaken to show the benefit of such mitigation. Mitigation can include avoiding risk (e.g., land-use planning); removing risk (e.g., cleaning); changing the likelihood (e.g., increasing insulation); or retaining risk with informed decision (e.g., monitoring) (Wardman et al., 2012).

6.6.1 Crisis response – Mt. Ruapehu case study

While our risk assessment shows areas of likely disruption and damage for two return periods, actual impact severity depends on which volcano erupts and the wind conditions at the time. For example, if Mayor Island erupts when the wind is blowing towards the east, no electrical infrastructure will be impacted as tephra will be deposited in the ocean; however, if Mt. Taranaki erupts with the same wind conditions, tephra could potentially impact all electrical infrastructure in the lower North Island. Using our fragility functions and risk assessment methodology, transmission disruption for a specific tephra fall scenario can be estimated. This demonstrates the potential application of this method as a near real-time predictive impact assessment tool to identify areas most at risk and to direct mitigation actions to appropriate locations. The methodology would utilise tephra fall hazard layers from forecast models immediately prior to or after an eruption or from initial field-mapped tephra thicknesses.

To illustrate this concept we conducted a risk assessment for the electrical transmission network for three historic eruptions (11 October 1995, 14 October 1995 and 17 June 1996) from Mt. Ruapehu. In total, these eruptions deposited at least 36×10^6 m^3 of tephra over the central and eastern North Island, up to 200 km from source (Cronin et al., 1998). Figure 6.12 shows the isopach maps for these three eruptions, the modelled probability of insulator flashover and ISs for substations and generation sites. Due to the thin deposits all substations are at IS_0 and one generation site during the 11 October 1995 and 17 June 1996 eruptions is estimated to experience IS_1 (Figure 6.12). During both the 1995 eruptions (Figure 6.12A), there is an increased probability (0.2–0.4) of insulator flashover on transmission lines to the east of Mt. Ruapehu, although no flashovers were reported during these eruptions. However, during an eruption on 25 September 1995 (isopach map unavailable but dispersal was similar to the 14 October 1995 eruption), 3 mm of wet tephra was deposited on 220 kV transmission lines near the base of Mt. Ruapehu (Wardman et al., 2012), causing insulator flashover and supply disruptions (Johnston et al., 2000; Wardman et al., 2012). This location is consistent with the increased likelihood of insulator flashover in Figure 6.12A.

6.7 Conclusions

This study presents a probabilistic tephra fall risk assessment for the high voltage electrical transmission network in the North Island, New Zealand. The probabilistic tephra fall hazard model developed in Chapter 5 is used to obtain the tephra thicknesses for electrical assets across the North Island for the 500 and 2,500 year return periods.

To calculate the vulnerability of electricity transmission assets we derive fragility functions to describe the probability of an asset being in one of four impact states as a function of tephra thickness. Functions are derived for the first time for generation sites (hydroelectric, thermal and geothermal), substations and transmission lines. Data from post-eruption impact assessments, laboratory experiments and expert judgment are used to derive these functions. The derived functions are subject to uncertainty as they are derived from a limited number of post-eruption impact assessments of mixed electricity asset typology. Given the limited impact data and the spatial scale of the assessment, i.e., the whole North Island, our vulnerability assessment is the most appropriate approach.

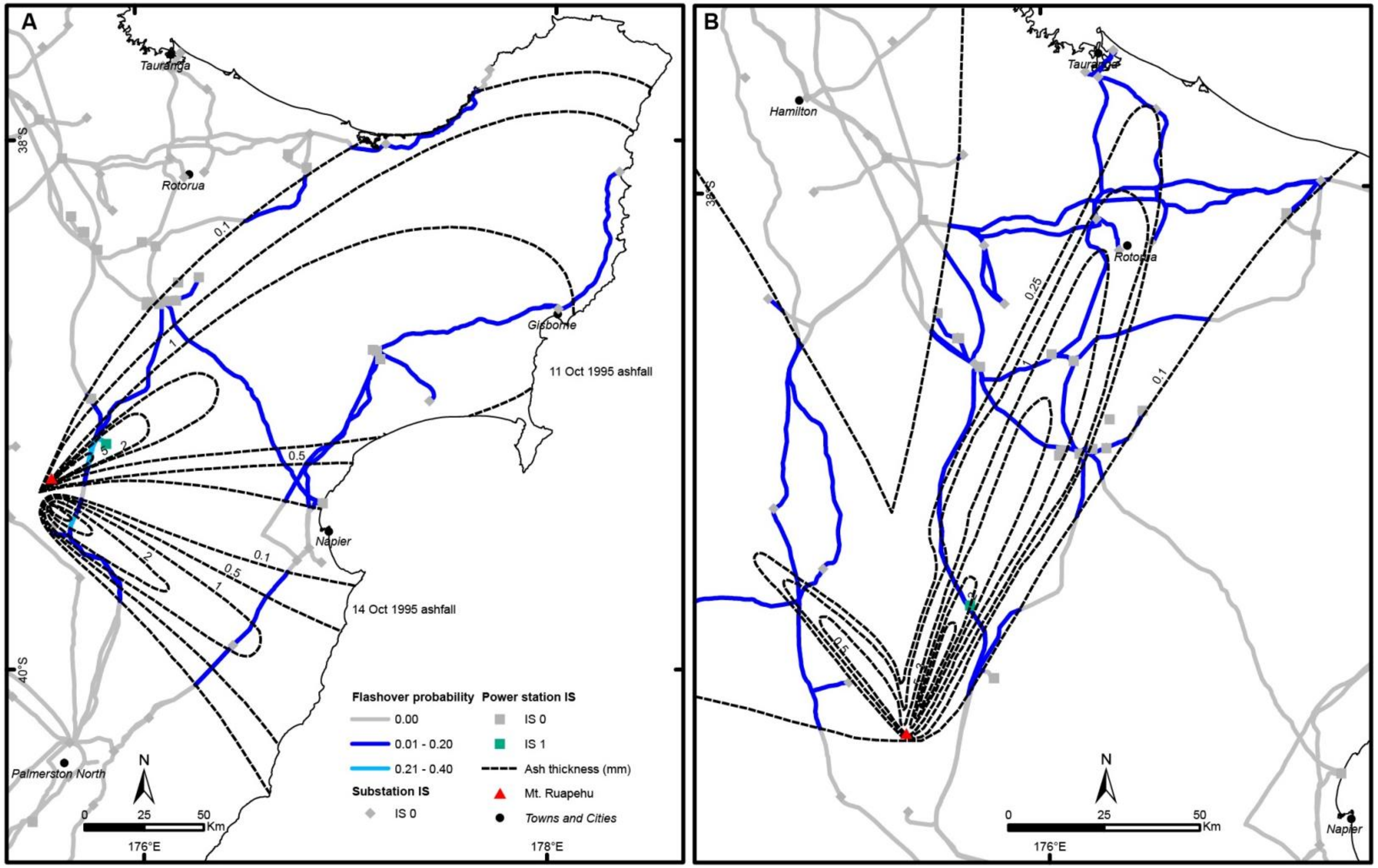


Figure 6.12: Risk assessment for electrical transmission assets for three historic eruptions from Mt. Ruapehu (red triangle). **A** isopach map of the 11 and 14 October 1995 tephra falls and corresponding risk to electrical assets. **B** isopach map of the 17 June 1996 tephra fall and corresponding risk to electrical assets. Main towns and cities indicated with circles. Isopach data from Cronin et al. (1998).

Combining modelled tephra thickness with the appropriate fragility function, the risk to the electricity transmission network is estimated. For a given tephra thickness, an electrical asset can be in one of four impact states governed by the probabilities given by the fragility functions. Therefore, for each tephra thickness a weighted average of 1,000 randomly generated impact states is taken to find a discrete impact state for each asset for each return period. For both the 500 and 2,500 year return periods, the highest risk and potential impact is to electrical sites immediately east of Mt. Ruapehu and Tongariro in the central North Island. In this region transmission lines are likely to suffer insulator flashover (IS_1) and substations and generation sites will be in IS_3. There is also an elevated risk of impact ($\geq IS_2$) further east towards the east coast and in the Napier and Gisborne regions. The risk is highest in these regions because Mt. Ruapehu and Tongariro are the most active (i.e., highest annual eruption probabilities) volcanoes and because the predominant wind direction is towards the east, therefore tephra dispersal is most common to the east. As the return period increases to 2,500 years, there is increased risk to the east of Mt. Taranaki, as larger and infrequent eruptions from this volcano contribute to the tephra fall hazard. The lowest risk to the electricity transmission network is towards the north and south of the North Island, where tephra thicknesses likely to cause impacts are less probable. However, electricity supply to these regions could be disrupted, as any occurrence of insulator flashover can disrupt electricity supply on entire transmission circuits. Over a 500 year return period, the high probability of insulator flashover in the central North Island leads to a high likelihood of disruption of critical north-south transmission lines between Palmerston North and Whakamaru, leading to possible widespread disruption.

This assessment helps to identify locations where mitigation could be implemented to reduce potential impacts from future eruptions and tephra falls. Mitigation actions could include increasing insulation on transmission lines, changing insulator designs, moving substations inside and developing plans and methods for the clean-up of tephra immediately after an eruption. Our assessment shows that mitigation should be considered on the transmission lines between Palmerston North and north of the TVC, and lines in the Napier region as there is a high risk of insulator flashover on these lines. However, mitigation actions should be trialled before implementation and a cost-benefit analysis should be undertaken first. Overall risk reduction will depend on the level of mitigation used and where it is implemented.

Our risk assessment can be used for specific eruption scenarios, for example during a future eruption. Utilising tephra fall hazard layers from tephra fall forecast models immediately prior to or after an eruption or from initial field-mapped tephra thickness, we can use our model as a near real-time predictive impact assessment tool. The utility is that it will direct end-users to locations likely to be impacted by tephra and locations where mitigation, such as cleaning, should be prioritised. Using our model in conjunction with electricity network analysis, disruption to the network can be minimised during a volcanic eruption.

6.8 Acknowledgements

We gratefully acknowledge funding support from Transpower New Zealand Ltd. (TW), DEVORA (GW, TW, NID), Ministry of Business, Innovation and Employment Natural Hazard Research Platform contract C05X0804 (TW and JC), Mason Trust (GW), Royal Society of New Zealand (Canterbury Branch) travel grant (GW), GNS Science and the Earthquake Commission.

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Chapter Seven – Conclusions and future research

7.1 Thesis overview

The aim of this thesis is to quantitatively assess the vulnerability of critical infrastructure sectors to volcanic hazards. This aim is addressed through six key thesis objectives:

1. Review and identify known impacts to critical infrastructure sectors from volcanic eruptions within the last 100 years (Chapter 2).
2. Identify volcanic hazard impact mechanisms and categorise infrastructure disruption and damage into standardised impact intensity classes (Chapter 2).
3. Develop a database to store volcanic impact data and facilitate the collection of standardised post-eruption impact data for future eruptions (Chapter 3).
4. Establish a methodological framework for the quantification of infrastructure vulnerability to volcanic hazards using vulnerability and fragility functions (Chapter 4).
5. Derive vulnerability and fragility functions for tephra fall impacts to critical infrastructure using the volcanic vulnerability framework (Chapter 4).
6. Utilise fragility functions to assess the tephra fall risk to the electrical transmission network in the North Island of New Zealand using a new probabilistic tephra fall hazard model (Chapters 5–6).

7.2 Synthesis

The ultimate goal of volcanic risk management is to reduce consequences of volcanic eruptions, first by saving lives and next by minimising societal impacts. Through a comprehensive study quantifying volcanic impacts to critical infrastructure, this thesis provides a pathway and catalyst for volcanic risk scientists to achieve this goal. This thesis has demonstrated that a range of complex, and at times widespread and cascading, consequences can occur to critical infrastructure impacted by volcanic hazards (Chapter 2). The majority of available volcanic impact data for critical infrastructure is qualitative, precluding its application in probabilistic risk assessments models currently being used by practitioners for volcanic disaster risk management, particularly for loss estimation and infrastructure management.

This thesis contributes to the improvement of volcanic vulnerability assessment in three ways.

First, this thesis provides an extensive review of volcanic impacts to critical infrastructure sectors for all volcanic hazards using all available literature and post-eruption impact assessments (Chapter 2). This is the first such review since Blong (1984) and further advances the volcanic research community's understanding of volcanic hazard impacts to critical infrastructure sectors.

Second, using the review of volcanic impacts to critical infrastructure, and more robustly analysing the range and type of impacts which critical infrastructure sustain during volcanic eruptions. This thesis provides a volcanic impact classification system which can be used to categorise infrastructure impacts from future eruptions based on impact and volcanic hazard intensity.

Third, this thesis provides a methodological framework to quantitatively assess the vulnerability of critical infrastructure sectors to volcanic hazard impacts (Chapter 4)—until now there has been no such standardised method to assess infrastructure vulnerability in volcanology. This framework draws on more advanced vulnerability assessment approaches from other natural hazard fields and outlines a method to classify infrastructure impacts, such that volcanic vulnerability and fragility functions can be derived to quantitatively relate impact intensity to volcanic hazard intensity.

While I use the framework to derive fragility functions for some infrastructure sectors impacted by tephra fall (Chapter 4) and utilised them in a risk assessment (Chapter 6), a key contribution of this thesis is the framework itself.

There are two main benefits of developing this volcanic vulnerability framework.

First, this framework is needed to advance quantitative volcanic vulnerability assessments to the same level of detail as volcanic hazard assessment, so both can be used in quantitative probabilistic volcanic risk assessments. The benefit of conducting quantitative volcanic risk assessments is that the vulnerability and risk at different infrastructure sites can be readily compared and uncertainty accounted for. This allows infrastructure operators to make informed risk-based decisions about the most appropriate volcanic risk reduction treatments for a particular situation. Cost-benefit analyses, which back these decisions, are greatly improved with robust quantitative vulnerability and risk data. In addition, these quantified volcanic risk assessments feed into wider governmental and international policies regarding sustainable development and infrastructure performance, a priority of the United Nations Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015).

Second, the development of this framework provides a pathway for volcanic risk scientists to improve critical infrastructure vulnerability assessments such that infrastructure vulnerability is more robustly understood and ultimately progress towards quantitative volcanic risk assessments. Using the framework, including data collection guidelines (Chapter 3), researchers can continue to refine infrastructure impacts based on volcanic hazard intensities; provide volcanic preparedness and response advice to infrastructure operators; and derive infrastructure vulnerability and fragility functions, further advancing the capabilities of volcanic vulnerability and risk assessments. Feeding this advanced vulnerability knowledge into volcanic risk assessments for infrastructure, such as that conducted in Chapter 6 or more integrated assessments which consider all infrastructure in a city (e.g., the DEVORA project; DEVORA, 2015), will greatly benefit volcanic disaster risk reduction.

7.3 Future research

Future research should further explore the vulnerability of critical infrastructure to volcanic hazards to develop a comprehensive understanding which can be utilised for volcanic risk reduction. Areas of potential future research are highlighted below.

Volcanic vulnerability assessment for critical infrastructure

- Continued quantitative vulnerability research for critical infrastructure sectors and components impacted by volcanic hazards. The focus should be on utilising the vulnerability framework outlined in Chapter 4 to derive and improve suites of vulnerability and fragility functions for all critical infrastructure sectors and all volcanic hazards. Advances in volcanic vulnerability assessment leads to improved volcanic risk assessment and reduction.
- Link physical vulnerability (damage and disruption) to economic loss and/or functional downtime. This provides infrastructure operators with a broader representation of likely impacts from volcanic hazards. This information is a vital input for volcanic risk reduction, cost-benefit analyses, and prioritisation.
- Consideration of multiple (concurrent and sequential) volcanic hazards in vulnerability assessments. Currently the influence that multiple volcanic hazards have on vulnerability and resilience is poorly understood and further research is needed. This could be achieved by thoroughly investigating multi-hazard impacts from field investigations or through the combination of different volcanic hazard-based fragility functions. This information will allow

more realistic vulnerability assessments to be conducted which account for multiple volcanic hazards, typical of volcanic eruptions.

- Investigation of vulnerability changes over the course of prolonged eruptions. Long-lasting eruptions are likely to cause ongoing impacts which cumulatively may lead to higher vulnerability than discrete eruptions. Infrastructure operator actions (e.g., ongoing clean-up) should also be considered in the modification of vulnerability as well as remobilisation of unconsolidated tephra deposits.
- Conducting site specific volcanic vulnerability assessments for infrastructure sectors. Because each infrastructure site has unique design, operational and functional requirements, site specific vulnerability assessments are required to account for how these factors influence vulnerability to volcanic hazards. These site specific assessments will provide more appropriate vulnerability information with which to base mitigation treatment on, than would regional or global volcanic vulnerability assessments.

Volcanic vulnerability data for critical infrastructure

- Continued and ongoing post-eruption impact assessments for any future eruptions will increase the availability of impact data for volcanic vulnerability assessments. These assessments should not only focus on general observations of impacts, but should forensically document all impacts, specifically recording volcanic hazard and impact intensities for use in quantitative vulnerability assessments. These assessments must investigate volcanic impacts to all infrastructure assets, systems and components while also balancing between assessment scale, available time and researcher expertise. Post-eruption impact assessments must document impact tolerance (i.e., where detrimental impact did not occur), so a representative sample of all volcanic hazard-infrastructure interactions for each eruption is obtained. Post-eruption assessments should follow the standardised impact assessment guidelines and populate the Critical Infrastructure Volcanic Impacts Database presented in Chapter 3.

- Continued laboratory experimentation of critical infrastructure components and systems to systematically investigate vulnerability over a range of volcanic hazard intensities. These experiments should focus towards informing infrastructure sector design guidelines, operational codes and mitigation approaches such that infrastructure operators can prepare for and restore their systems efficiently and effectivity after volcanic eruptions.
- Increased use of expert knowledge to derive volcanic fragility and vulnerability functions. Larger expert elicitation processes which include experts from the volcanology community and infrastructure operators and follow standard procedures should be undertaken. Using a larger number of experts from both fields should result in more appropriate volcanic vulnerability estimates.

Volcanic hazard assessment

- Continued improvement of probabilistic volcanic hazard models such that they output multiple hazard intensity metrics (e.g., tephra grainsize, tephra particle soluble salt chemistry, hazard duration). These additional parameters are useful for assessing infrastructure vulnerability as multiple volcanic hazard properties commonly combine to cause impacts.
- Development of numerical volcanic hazard models which consider multiple volcanic hazards over various timeframes, i.e., models should consider whole eruption sequences. These types of models will allow the use of volcanic vulnerability assessments which consider multiple volcanic hazards and impact duration to be used in volcanic risk assessments, further refining these assessments.

Critical infrastructure interdependencies

- The inclusion of critical infrastructure interdependencies in volcanic vulnerability and risk assessments. Interdependency influences vulnerability because cascading failures can cause disruption to other sectors (Rinaldi et al., 2001). Interdependencies can be complex and collaboration between volcanic risk scientists and infrastructure operators is required to understand them and deliver appropriate volcanic risk assessments.

Critical infrastructure operator volcanic hazard awareness

- Increasing infrastructure operator's awareness of volcanic hazards and their impacts. Volcanic risk scientists should also demonstrate the value of volcanic risk management by providing useful and understandable volcanic vulnerability, preparedness and response resources. For example, a continuation of the volcanic ashfall infrastructure preparedness poster series of Wilson et al. (2014). This should be achieved through collaborative partnerships between volcanic scientists and infrastructure operators.

Such future research avenues follow the pathway envisaged by this thesis towards a more thorough and rigorous assessment of volcanic vulnerability leading towards comprehensive volcanic risk assessment, management and reduction.

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Appendix A – Volcanic fragility function review

A.1 Fragility functions

In volcanology there are fewer existing vulnerability and fragility functions than other natural hazard fields. There are a number of reasons for this: (1) volcanic hazards are not often considered in infrastructure hazard assessments; (2) volcanic hazards are rarely considered in catastrophe modelling; (3) there are no building or infrastructure design codes for volcanic impacts which would prompt the derivation of functions; and (4) volcanic eruptions are infrequent events on human and infrastructure timeframes (Douglas, 2007; Wilson et al., 2012). Despite the challenges, several vulnerability and fragility functions have previously been developed (in addition to those derived in Chapter 4) for volcanic hazards (Table A.1) which are reviewed below. In addition, hazard intensity thresholds for critical infrastructure impacts have been derived for tephra fall (Chapter 2; Jenkins et al., 2014) and for pyroclastic density currents (Spence et al., 2004a).

Table A.1: Existing critical infrastructure fragility and vulnerability functions developed for different volcanic hazards. No published peer-reviewed fragility functions for water supply, communication networks or lava flows were found. Table repeated from Chapter 2.

Infrastructure sector	Tephra fall	PDC	Lahar
Electrical supply	a		
Wastewater networks	b		
Transportation networks	b		
Buildings	b, c, d, e, f	d, g, h	g
Critical components	i		

[a] Wardman et al. (2012); [b] Kaye (2007); [c] Spence et al. (2005); [d] Zuccaro et al. (2008); [e] Jenkins and Spence (2009); [f] Maqsood et al. (2014); [g] Zuccaro and De Gregorio (2013); [h] Spence et al. (2007); [i] Wilson et al. (2012).

A.1.1 Buildings

A.1.1.1 Tephra fall impacts

Fragility functions for tephra fall induced roof collapse have been developed by Paton et al. (1999); Spence et al. (2005), Kaye (2007), Zuccaro et al. (2008), Jenkins and Spence (2009) and Maqsood et al. (2014); reviewed below in chronological order. Paton et al. (1999) estimated the mean damage ratio of building damage for New Zealand buildings based on two roof categories. Damage ratios for lightweight roofs were based on roof damage from Rabaul (Blong and McKee, 1995) and while those for concrete roofs were based on interpretation of gravity collapse loads from the New Zealand building codes. Spence et al. (2005) reviewed failure calculations, mechanical experiments and post-eruption impact assessment observations from a number of studies (e.g., Schriever and Hansen, 1964; Spence et al., 1996; Pomonis et al., 1999; Blong, 2003) to inform tephra load fragility functions for Neapolitan (Italy) roofs. For these roofs, Spence et al. (2005) established five vulnerability classes with mean collapse probabilities derived from calculations and experiments, and standard deviations based on expert judgment. Spence et al. (2005) modified these functions for more general European roof typologies by developing collapse limits for four European roof vulnerability classes. Zuccaro et al. (2008) refined the Neapolitan roof fragility functions with mechanical load experiments, numerical analysis and statistical calculations (Figure A.1B). Jenkins and Spence (2009) developed fragility functions for roof damage for five African and Asian roof typologies. Kaye (2007) assessed the vulnerability of New Zealand roofs to tephra fall using two vulnerability classes, long (>15 m) and short (<15 m) roof spans. Kaye (2007) vulnerability functions are linear and relate thickness of wet ash to a damage ratio of cost of repair relative to cost of replacement. Maqsood et al. (2014) derived vulnerability functions for tephra fall induced damage of buildings for the United Nations Global Assessment Report 2015 (GAR15). Functions were derived for 32 global building typologies using an expert judgment process. Functions plot tephra load as a function of damage index, the ratio of repair cost to replacement cost. All of these functions consider the probability of roof collapse and do not consider other damage states, as collapse limits are easier to establish than limits for lesser damage states.

A.1.1.2 Pyroclastic density current (PDC) impacts

Fragility functions for PDC induced building damage have been derived by Jenkins and Spence (2009) and Zuccaro and De Gregorio (2013). These functions have been derived by reviewing and refining previous works which document vulnerability using analytical techniques, comparison with nuclear explosions (Valentine, 1998) and from post-eruption impacts (Spence et al., 2004a; Spence et al., 2004b; Spence et al., 2005; Zuccaro et al., 2008). Given that vulnerability depends on building structure and design, Zuccaro et al. (2008) defined six structural and eight non-structural vulnerability classes applicable to Neapolitan buildings. For each structural class, fragility functions were defined for five damage states using mechanical and numerical models, experimental data, post eruption observations, updated hazard models and the Spence et al. (2004b) derived fragility functions for non-structural damage. Resulting fragility functions gave the probability of exceedance for each damage state as a function of PDC dynamic pressure (Figure A.1C). Jenkins and Spence (2009) derived fragility functions for the probability of failure (i.e., the highest damage state) for four African and Asian building typologies as a function of dynamic pressure based on previous studies.

A.1.1.3 Lahar impacts

Zuccaro and De Gregorio (2013) derived fragility functions for lahar impacts to Neapolitan buildings. Six structural vulnerability classes are defined based on building strength and six non-structural vulnerability classes for infill walls and openings (windows and doors). Functions were derived for different combinations of structural and non-structural vulnerability classes by numerically and experimentally assessing impacts at given lahar velocities (Figure A.1A). These functions differ from others; a damage state scale on the y-axis is used instead of the more common probability of exceedance. As a result there are no probabilities associated with the damage occurrence for these functions; despite this, these functions provide a quantitative estimate of sustained building damage resulting from lahars.

A.1.2 Electricity transmission

Laboratory experiments by Wardman et al. (2012) and Wardman (2013) produced data to evaluate the probability of tephra induced flashover of electrical insulators in dry and wet conditions. Experimental, post-eruption impact assessments and expert judgment data were used to develop a fragility function for the probability of flashover as a function of wet tephra thickness. Dry tephra is less electrically conductive than wet tephra; therefore all dry tephra thicknesses have no probability of flashover. Wardman et al. (2012) acknowledges that there are a number of other factors that influence flashover probability and further research should be conducted to understand these factors.

A.1.3 Other infrastructure

Kaye (2007) developed vulnerability functions for stormwater and road networks for New Zealand’s RiskScape assessment tool. For stormwater pipes, the damage ratio increases linearly as tephra thickness increases until 100 mm when the damage ratio equals 1 (i.e., repair cost is greater than replacement cost). The road function is based on expected clean-up costs and assumes a linear increase in vulnerability until 1,000 mm tephra thickness were the damage ratio equals 1. Kaye (2007) notes that these functions have been developed in the absence of detailed vulnerability data and that new data can assist to refine the functions.

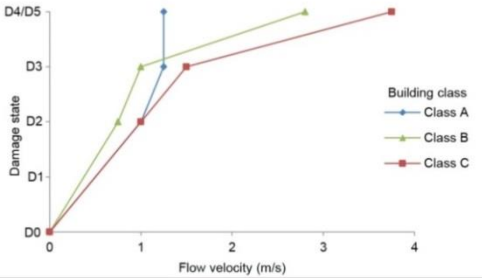
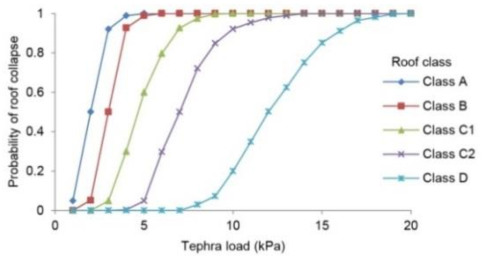
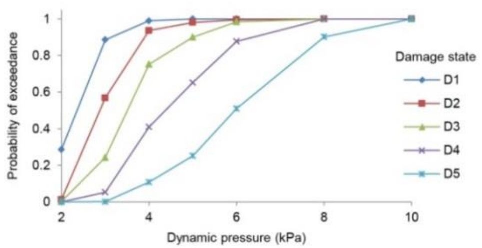
Type	Fragility function example	Description
A		**Damage state vulnerability function** • Estimates damage state reached as a function of hazard intensity for different infrastructure vulnerability classes. • Requires the least amount of data. • Can be produced if damage thresholds are known. Example: Lahar vulnerability curves for different building classes showing damage state reached as a function of lahar velocity (reprinted from Zuccaro and De Gregorio (2013) with permission from Springer). • Derived from numerical and experimental data.
B		**Probability of highest damage state exceedance** • Estimates the probability of the highest damage state exceedance as a function of hazard intensity for different infrastructure vulnerability classes. • Used when there is only sufficient hazard intensity data for the highest damage state (generally collapse). Example: Probability of reaching partial or total roof collapse as a function of tephra load for European roofs (reprinted from Zuccaro et al. (2008) with permission from Elsevier). • Derived from failure calculations, mechanical experiments, post-eruption impact assessments and expert opinion.
C		**Probability of damage state exceedance** • Estimates the probability of damage state exceedance as a function of hazard intensity. • Used when there is sufficient hazard intensity data for all damage states. • Requires the most amount of statistically valid data. Example: PDC fragility functions for Neapolitan building class A, showing probability of exceeding each damage state as a function of PDC dynamic pressure (reprinted from Zuccaro and De Gregorio (2013) with permission from Springer). • Derived from mechanical and numerical models, experimental data, limited post-eruption observations and previously derived fragility functions.

Figure A.1: Examples of common volcanic fragility functions. **A** damage state function; **B** probability of exceeding highest damage state; and **C** probability of damage state exceedance.

A.1.4 Electronic equipment

Laboratory experiments conducted by Wilson et al. (2012) subjected laptop computers to semi-continuous tephra fall for seven days while assessing computer performance. Throughout all experiments no laptops completely failed and only three had minor problems (overheating, minor abrasion). Using the difference between pre- and post-tephra performance and user input (keyboard, mouse) usability tests, the decrease in usability as tephra thickness increases was used as a proxy for function loss. A vulnerability function is fit to the data using a power function (Figure A.2). The method used to derive this function is different to that of Chapter 4 as it does not consider different impact states.

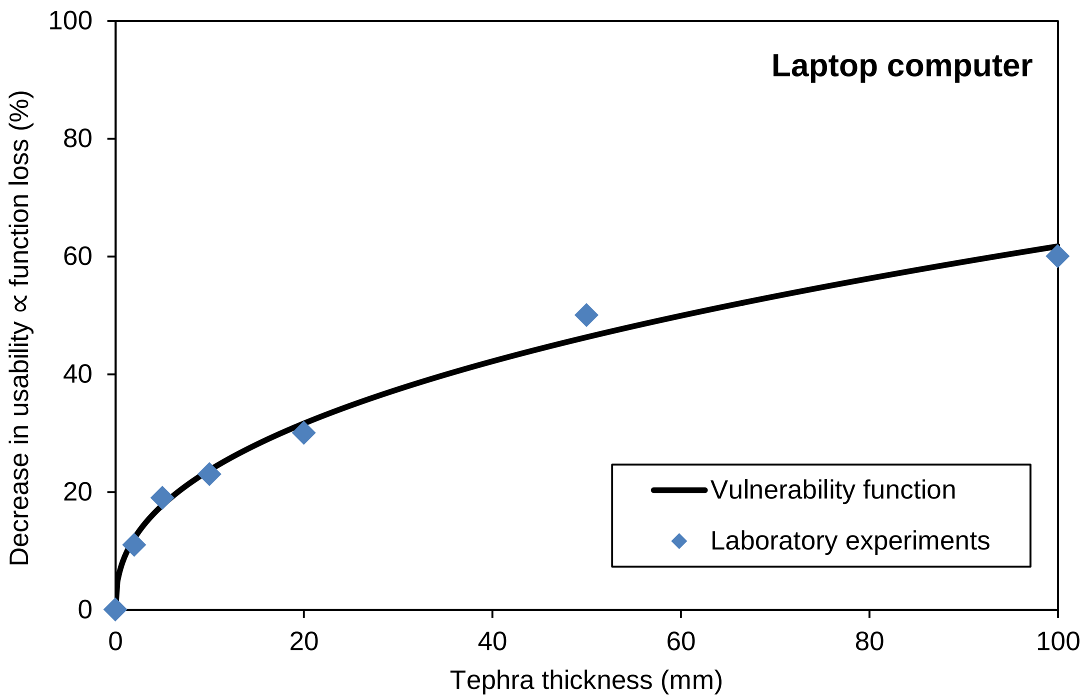


Figure A.2: Vulnerability function for computer systems showing changes in functionality as a function of tephra thickness. Experimental data from Wilson et al. (2012).

A.2 References

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Appendix B – Post-eruption impact assessment guidelines

Additional guidelines, questions and data for airports, road transportation, buildings, water supply and wastewater networks which can be used to guide and conduct post-eruption impact assessments. These guidelines are based on the experience of the New Zealand Volcanic Impacts Study Group researchers. See Chapter 3 for further discussion.

Table B.1: Data to be documented for source volcano and eruption.

Aspect	Assessed item
Source volcanoes	Volcano number.
	Primary volcano name.
	Latitude, longitude, sub-region, region, country.
	Primary volcano type.
	Last known eruption.
Eruptions	Eruption code – 3 letters from volcano name followed by 2 digit year.
	Eruption start and end dates, or indicate if ongoing.
	Environmental conditions at time of eruption (rain, wind direction).
	Volcanic Explosivity Index (VEI), magnitude and plume height.
	Which hazards were produced?
	Which infrastructure were impacted?

Table B.2: Recommended post-eruption impact assessment questions and data for general airport and aircraft characteristics and impacts.

Aspect	Assessed item
Airport site	Name of company operating airport.
	Town airport is located within.
	Latitude, longitude, distance from volcano.
	Is the airport for domestic, international, cargo or military flights?
	Number of domestic, international, cargo or military flights per day.
	Number of passengers per day.
	Number of runways and what are their surfaces?
	Airport's normal operating hours.

Aspect	Assessed item
	Number of terminal buildings, support buildings (hangers).
	What communication systems are used at the airport?
	Has the site experienced volcanic hazards before and did that experience help this time?
	Describe any volcanic hazard contingency or preparedness plans that were in place pre-eruption.
	Describe any contingency plans that been developed since the eruption.
	Have any volcanic specific mitigation actions been implemented to reduce impacts?
Airport impacts	Was a warning received before the eruption? Who provide the warning? How much warning time?
	Describe any steps that were taken to prepare for the eruption.
	Was airport tolerant to eruption and hazard(s)?
	List the impacts observed at the airport.
	What is the impact level (using Tables 2.11-2.14)?
	What hazard caused the impact and what was the HIM value?
	How were airport communication systems impacted?
	How was the runway and/or paved surfaces impacted?
	Did the airport close? How long was the airport closed? What caused the closure? How many flights disrupted? Estimated lost revenue?
	Did all airlines return after closure, if so how long after closure?
	Time to return to pre-eruption passenger and plane numbers?
	Describe how any impacts were managed (closure, repair, additional maintenance, clean up).
	Describe any repair undertaken.
	Describe clean-up operations undertaken.
	Describe any interactions with other agencies.
	Are there any lessons learnt or procedures that would help future eruption response?
Aircraft impacts	If aircraft were damaged, were they in flight or at an airport?
	What type of aircraft?
	Time into flight when impacts occur.
	List observed impacts.
	What is the impact level (using Tables 2.11-2.14)?
	What hazard caused the impact and what was the HIM value?
	How were impacts sustained in-flight and on the ground managed?
	If aircraft were on the ground, were they protected from tephra fall? If so, how were they protected?
	How were aircraft repaired or cleaned? How long did repair take? What was the cost of the repair?

Table B.3: Recommended post-eruption impact assessment questions and data for general road network and vehicle characteristics and impacts.

Sub-sector	Assessed item
Road network	Is this assessment for a small road section, a whole road or the whole network?
	Name of road?
	Name of company who owns road?
	Latitude, longitude, distance from volcano.
	Total length of roads in network or section of interest.
	What type of road is it (motorway, highway, surface street) and what materials is it made from?
	What is the condition of the road surface?
	Grade/slope of road
	If there are bridges, what type of bridges are they?
	What type of drainage is there on the road?
	Are there painted lines on road?
	What type of street lights, traffic lights and signs are there?
	Number of vehicles per day on road and predominant vehicle type.
	Has the site experienced volcanic hazards before and did that experience help this time?
	Describe any volcanic hazard contingency or preparedness plans that were in place pre-eruption.
	Describe any contingency plans that been developed since the eruption.
	Have any volcanic specific mitigation actions been implemented to reduce impacts?
	Has the site experienced volcanic hazards before and did that experience help this time?
Road impacts	Was a warning received before the eruption? Who provide the warning? How much warning time?
	Describe any steps that were taken to prepare for the eruption.
	Was the road network tolerant to eruption and hazard(s)?
	List of impacts to the road network.
	What is the impact level (using Tables 2.11-2.14)?
	What hazard caused the impact and what was the HIM value?
	Was road closed, what caused the closure, how long was the closure?
	What was the level of reduced traction?
	Were there any vehicle crashes related to the eruption and/or hazard(s)?
	Number of vehicles on road during the eruption.
	What was the behaviour of drivers driving during eruption?
	Distance to furthest object which can be seen?
	Are vehicles causing tephra remobilisation?

Sub-sector	Assessed item
	Are there any impacts to lights, signs or painted road markings?
	Were the roads cleaned, if so, how?
	Are there any lessons learnt or procedures that would help future eruption response?
Vehicle impacts	Is this assessment for an individual vehicle or multiple vehicles?
	Location of the vehicle.
	Was the vehicle stationary or driving at the time of impact?
	Type of vehicle?
	List impacts to vehicle.
	What is the impact level (using Tables 2.11-2.14)?
	What hazard caused the impact and what was the HIM value?
	Additional comments about vehicle impact.
	How were impacts repaired, how long did repair take and what was the repair cost?
	Was there any increased maintenance of vehicles?
	Describe any increases in maintenance of vehicles.
	Are there any lessons learnt or procedures that would help future eruption response?

Table B.4: Recommended post-eruption impact assessment questions and data for general building characteristics and impacts.

Sub-sector	Assessed item
Building site	Town or city were building is located.
	Latitude, longitude, distance from volcano.
	Orientation of building with respect to north.
	Description what the building is used for (use classification).
	Building typology (structure, roof, walls) description and age.
	Number, size and materials of openings (windows, doors).
	Roof pitch in degrees from horizontal.
	Description of guttering (size, material).
	Floor height above ground level.
	Footprint area.
	Condition of building prior to eruption (if known).
Building Impacts	List of impacts to non-structural elements.
	List of impacts to structural elements.
	What is the impact level (using Tables 2.11-2.14)?
	What hazard caused the impact and what was the HIM value?
	Description of both non-structural and structural impacts.
	Description of any roof corrosion including severity, and percentage corroded.

Sub-sector	Assessed item
	Description of any ballistic damage to roof including hole diameter, percentage of roof with holes.
	Description of any damage to guttering.
	Is there any abrasion of windows, window frames, wall cladding?
	Is the building habitable?
	Description of any repair or clean-up undertaken including methods and costs.

Table B.5: Recommended post-eruption impact assessment questions and data for general pipe network characteristics and impacts.

Sub-sector	Assessed item
Pipe network	What sector does pipe network belong (water supply, wastewater)?
	Is this assessment for an individual section, multiple sections or the whole network?
	Name of the site.
	Operating company.
	Town or city site is located within.
	Latitude, longitude, distance from volcano.
	Area serviced by pipe network.
	Total length of pipes in network or section of interest.
	Pipe materials, diameter, thickness, depth below ground or above ground support.
	Has the site experienced volcanic hazards before and did that experience help this time?
	Describe any volcanic hazard contingency or preparedness plans that were in place pre-eruption.
	Describe any contingency plans that been developed since the eruption.
	Have any volcanic specific mitigation actions been implemented to reduce impacts?
Pipe impacts	Was a warning received before the eruption? Who provide the warning? How much warning time?
	Describe any steps that were taken to prepare for the eruption.
	Was the pipe network tolerant to eruption and hazard(s)?
	List of impacts to the pipe network.
	What is the impact level (using Tables 2.11-2.14)?
	What hazard caused the impact and what was the HIM value?
	Where pipes blocked? Percentage decrease in pipe throughput? How long were pipes blocked for?
	Thickness of tephra material in catchpits. How did material enter the pipe network?
	Was there flooding as a result of pipe damage and/or blockage?
	How were impacted pipes repaired or cleaned, how long did repair take, what was the repair cost?

Sub-sector	Assessed item
	Are there any lessons learnt or procedures that would help future eruption response?

Table B.6: Recommended post-eruption impact assessment questions and data for general water supply network characteristics and impacts.

Sub-sector	Assessed item
Water supply site	Is this assessment for an individual site, multiple sites or all sites?
	Name of the site.
	Operating company.
	Town or city site is located within.
	Latitude, longitude, distance from volcano.
	Number of people the treatment plant serves.
	Describe relationship with other treatment plants in the area.
	Water production rate of treatment plant.
	How much storage capacity does the system have?
	What are the water sources used?
	Is there an automatic shutdown for water intake structures? And what level is it shutdown?
	What is the depth of water intake structure (if in reservoir)?
	What is the normal turbidity range of the raw water and what is the operating turbidity level of the plant and what other raw water parameters are monitored?
	Description of the pre-screening process including intake filters.
	Do treatment plant and/or pumping stations have back up power supply and water storage capacity?
	How is water transported to treatment plant (gravity or pumps)?
	Number, type, capacity of pumps.
	Are pumps and/or well heads of groundwater systems covered or exposed?
	Is plant equipment housed indoors or outdoors?
	Description of treatment process.
	Is there an initial coagulation and/or flocculation addition step?
	Number of treatment units used and residence time through them.
	What monitoring of final water is undertaken?
	Describe the normal maintenance schedule.
	Has the site experienced volcanic hazards before and did that experience help this time?
	Describe any volcanic hazard contingency or preparedness plans that were in place pre-eruption.
	Describe any contingency plans that been developed since the eruption.

Sub-sector	Assessed item
	Have any volcanic specific mitigation actions been implemented to reduce impacts?
	Has the site experienced volcanic hazards before and did that experience help this time?
Water supply impacts	Was a warning received before the eruption? Who provide the warning? How much warning time?
	Describe any steps that were taken to prepare for the eruption.
	Was the site tolerant to eruption and hazard(s)?
	List of impacts to the water treatment site.
	What is the impact level (using Tables 2.11-2.14)?
	What hazard caused the impact and what was the HIM value?
	Was there any disruption to water treatment? What caused the disruption and how long did the disruption last?
	Were water intakes shutdown?
	Where there changes in turbidity, did the eruption affect turbidity removal, how was turbidity removed? Was coagulation and flocculation addition adjusted?
	Description of changes in water chemistry or biological growth.
	Did public report any unusual taste and/or discolouration of treated water? What advice was given to the public?
	Comments about changes in coagulation/flocculation.
	Did material arrive at the treatment plant, how much material and how did it enter the plant (pipes or direct air fall)?
	Which part of the plant did material primarily accumulate?
	How were filters maintained, repaired or cleaned?
	Did any uncovered equipment experience any problems?
	Did power remain at water treatment plant? How long was power unavailable?
	Did power remain at pump stations? How long was power unavailable?
	Was pumping able to continue throughout the eruption?
	Was there any abrasion to pump impellers, if so, when did it occur, what was the severity and how was it repaired?
	Percentage decrease in pumping efficiency due to pump damage.
	Was there any corrosion to metal surfaces, if so, when did it occur, what was the severity and how was it repaired?
	Was additional maintenance required?
	What additional maintenance was required?
	Was there any changes in water demand and how was it managed?
	Was emergency water supply used (e.g., tankers)?
	Describe how any impacts were managed (closure, repair, additional maintenance, clean up).

Sub-sector	Assessed item
	Describe clean-up operations undertaken.
	Describe any interactions with other agencies.
	Are there any lessons learnt or procedures that would help future eruption response?

Table B.7: Recommended post-eruption impact assessment questions and data for general wastewater characteristics and impacts.

Sub-sector	Assessed item
Wastewater site	Is this assessment for an individual site, multiple sites or all sites?
	Name of the site.
	Operating company.
	Town or city site is located within.
	Latitude, longitude, distance from volcano.
	Number of people the treatment plant serves.
	Describe relationship with other treatment plants in the area.
	Capacity of treatment plant, normal throughout and does throughput change with seasons?
	Is the wastewater network combined with the stormwater network?
	Does foreign material (e.g., sand) enter treatment plant, if so, what volume?
	What is the incoming suspended solid load in wastewater during normal conditions and rain storm conditions?
	Do treatment plant and/or pumping stations have back up power supply?
	Describe the treatment process including pre-screening, primary, secondary and tertiary treatment.
	Percentage of plant open to the atmosphere.
	What monitoring of treated waste is undertaken?
	Number, type, capacity of pumps.
	Describe the normal maintenance schedule.
	Has the site experienced volcanic hazards before and did that experience help this time?
	Describe any volcanic hazard contingency or preparedness plans that were in place pre-eruption.
	Describe any contingency plans that been developed since the eruption.
	Have any volcanic specific mitigation actions been implemented to reduce impacts?
	Has the site experienced volcanic hazards before and did that experience help this time?
Wastewater impacts	Was a warning received before the eruption? Who provide the warning? How much warning time?

Sub-sector	Assessed item
	Describe any steps that were taken to prepare for the eruption.
	Was the site tolerant to eruption and hazard(s)?
	List of impacts to the wastewater treatment site.
	What is the impact level (using Tables 2.11-2.14)?
	What hazard caused the impact and what was the HIM value?
	Was there any disruption to wastewater treatment? What caused the disruption and how long did the disruption last?
	Was the treatment plant shutdown at any point and for how long?
	Did material arrive at the treatment plant, how much material and how did it enter the plant (pipes or direct air fall)?
	Which part of the plant did material primarily accumulate?
	Change in solid load in raw wastewater after the eruption.
	How was material removed from pipes and tanks?
	Did any material enter drains and/or catchpits?
	Did power remain at water treatment plant? How long was power unavailable?
	Did power remain at pump stations? How long was power unavailable?
	Were there any overflows at pump stations?
	Was there any abrasion to pump impellers, if so, when did it occur, what was the severity and how was it repaired?
	Percentage decrease in pumping efficiency due to pump damage.
	Was there any corrosion to metal surfaces, if so, when did it occur, what was the severity and how was it repaired?
	What additional maintenance was required?
	Was any untreated (or slightly treated) waste discharged into the environment, how long did discharge last, what volume was discharged and where there any environmental issues or public concern?
	Describe how any impacts were managed (closure, repair, additional maintenance, clean up).
	Describe clean-up operations undertaken.
	Describe any interactions with other agencies.
	Are there any lessons learnt or procedures that would help future eruption response?

Appendix C – Impacts of the 2014 eruption of Kelud volcano, Indonesia, on infrastructure, utilities, agriculture and health

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Draft report submitted to GNS Science May 2015.
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